BBC RD 1994/17

Research and Development Report

Com^3: A Composite-Compatible Component coding system

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Research and Development Department
Engineering Division
THE BRITISH BROADCASTING CORPORATION

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Summary

*This Report describes a method for conveying a component video signal on a single cable in such a way that it may be passed through any existing composite studio equipment that has a bandwidth of approximately 9 MHz. The system was originally termed Extended Studio PAL, although it is now referred to as Composite Compatible Component (**Com^3**) in order to emphasise the quality difference it offers over PAL. It is particularly suitable for use with digital composite equipment operating at a sampling rate of four times the colour subcarrier frequency, such as D2 and D3 video recorders. The coding method yields a picture quality approaching that of CCIR Recommendation 601, without any crosstalk between luminance and chrominance. The absence of such artefacts and the additional horizontal resolution it offers compared with conventional PAL are particularly useful for working with widescreen 16:9 pictures. The coded signal is highly compatible with PAL, allowing mixing with conventional PAL and the use of existing studio monitors.*

The principle of Weston, or phase-segregated, PAL is used to form a signal in which the components are separated by phase. No temporal processing is used and therefore no motion artefacts are introduced. The propagation delay of a codec is about 8 lines, so compensating sound delays are not required. The higher frequencies of the coded signal are used to carry high-frequency luminance and chrominance detail, so the signal is tolerant to high-frequency losses. The principles are equally applicable to a system compatible with NTSC.

Experimental equipment has been constructed to implement the coding system, which has been used in field trials in a studio and an outside broadcast vehicle. These trials verified that existing PAL equipment can convey the coded signal with little or no impairment.

Issued under the Authority of

General Manager
Research & Development Department

Research & Development Department,
Engineering Division
BRITISH BROADCASTING CORPORATION

1994

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Com^3: A Composite-Compatible Component coding system

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1. INTRODUCTION

This Report describes a method for conveying a component video signal on a single cable in such a way that it may be passed through any existing composite studio equipment that has a bandwidth of approximately 9 MHz. Much existing analogue equipment has been found to be capable of conveying such wide-bandwidth signals with minimal loss. The new signal fully exploits the bandwidth available in digital composite equipment operating at 4f_{sc}* such as the D3 recorder. The wide bandwidth offered by such equipment is highly under-utilised at present.

The system** described here allows existing composite studio equipment, capable of passing such a bandwidth, to be used to produce a signal that can be decoded to give a quality approaching that of CCIR Rec. 601, without any of the footprints normally associated with a PAL signal. The coded signal is highly compatible with conventional PAL, allowing mixing with conventional PAL and the use of existing studio monitors. In future, a broadcaster using existing studios (with a composite infrastructure) may wish to produce component signals well-matched to wide-screen broadcasting methods — such as required for PALplus, D2MAC or emerging digital systems, for example. Now, only the coders need be replaced in conventional PAL-equipped studios, so avoiding a complete refurbishment with component equipment. Existing facilities based upon digital equipment operating at 4f_{sc}, such as D2 or D3 digital composite recorders, may also be used. However, if analogue interfaces to such equipment are used, some modifications to the filters in the ADC and DAC circuitry are desirable to ensure minimal losses at the upper end of the band. This is because the coding system fully exploits the bandwidth offered by the 4f_{sc} sample rate.

The basic requirement to package a component video signal onto a single cable without interaction between the components could, in theory, be met in several ways. A time-division multiplexing method like MAC could for example be used; however such a signal format would be difficult to monitor without the use of a special decoder, and mixer effects such as wipes would not work. A frequency-division multiplex signal would allow wipes to be used, since all information relating to a particular point in the picture would appear in the coded signal at the corresponding time instant; although there exists the possibility of interaction between components due to imperfect separation of frequency bands. The criterion of perfect separability can, however, be met by using carefully-chosen filter characteristics and sampling phases when forming the signal, using ideas from the area of sub-band coding.

In order for the signal to produce an acceptable picture on a normal PAL monitor, its spectrum below about 5.5 MHz should resemble conventional PAL. A method of producing a signal that allows perfect separation of chrominance and luminance while closely resembling conventional PAL has been known for some time. The method, called *phase-segregated* or *Weston Clean* PAL[1], is totally different from other forms of PAL coding such as comb filtering. Many PAL coding techniques rely on partitioning the spectrum of the coded signal between luminance and chrominance; at its simplest this can be viewed as removing those luminance frequencies that give rise to cross-colour, and those chrominance frequencies that cause cross-luminance. In contrast, Weston Clean PAL does not rely on removing such spectral components; instead, the luminance and chrominance signals are allowed to share spectrum in the coded signal and can be separated perfectly by their phase characteristics. One penalty of this approach is that the bandwidth of the luminance signal is limited to a value that can be supported by a sample rate of 2f_{sc}; this is lower than would be preferred for applications such as wide-screen production. Another penalty is that the chrominance signals must be subsampled vertically by a factor of two. The vertical chrominance resolution is therefore less than that of conventional PAL, although not by as much as this factor when compared to a line-delay PAL decoder. It is worth noting that standard PAL has excessive vertical chrominance resolution compared to horizontal resolution (by a factor of about three for a line-delay PAL decoder and a 16:9 display).

The spectrum above 5.5 MHz may be used in any way that is desired for enhancing the quality of the signal. The total bandwidth of the signal has been limited to approximately 8.8 MHz*. This value was chosen so that it could be recorded without loss on existing digital composite VTRs operating at a sample rate of $4f_{sc}$; therefore, approximately 3.3 MHz of additional bandwidth remains available. About 2.2 MHz of this bandwidth has been selected to carry additional luminance information; thereby providing a total luminance bandwidth essentially equal to that of CCIR Rec. 601. The remaining 1.1 MHz is used to enhance the chrominance, giving the system a chrominance bandwidth that, although somewhat reduced from that available in Rec. 601, provides equal horizontal and vertical resolution when a 16:9 display is used. The chrominance band in the coded signal therefore extends up to approximately 6.6 MHz, with the band between 6.6 MHz and 8.8 MHz carrying additional luminance information.

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* In this Report, the symbol f_{sc} is used to denote the PAL colour subcarrier frequency 4.43361875 MHz. The emboldened symbol $\mathbf{f}_{sc}$ is used to denote the *frequency vector* which results when the signal frequency of f_{sc} is combined with the scanning action and has principal horizontal components of 4.433... MHz and 72 cycles per active picture height.

** The system was originally termed *Extended Studio PAL*, although it is now called *Composite Compatible Component* (**Com^3**) to emphasise the quality difference it offers over PAL. Application has been made by Snell & Wilcox Ltd (who are licensing the system) to register **Com^3** as a trademark.

The resulting coding system conveys luminance with a bandwidth of 6.6 MHz (–6 dB) and chrominance with a bandwidth of approximately 2.2 MHz. The vertical chrominance bandwidth is restricted to approximately 70 c/aph**, due to the use of 2:1 vertical subsampling. The reduction in vertical chrominance bandwidth is the most significant difference between the performance of the coding system and that of Rec. 601. In this respect, it is worth noting that many present or proposed distribution media, such as MAC and some digital proposals, are unable to transmit vertical chrominance frequencies above this figure.

If the bandwidth of the coded signal is restricted to 5.5 MHz (for example, by a C-format recorder), the horizontal luminance and chrominance resolutions are reduced to approximately 5 MHz and 1 MHz respectively, but the system remains free of cross-effects.

The coding system does not rely on temporal, adaptive or non-linear processing. This ensures that linear mixing or cutting operations will not affect the picture quality. Furthermore, the absence of field delays allows the propagation delay through a coder or decoder to be kept low (each is about 4 lines), which removes the need for compensating sound delays.

Section 2 gives an explanation of the coding algorithm and Section 3 summarises the results of field trials of the system.

Although this Report concentrates on a PAL-compatible form of the system, the principles are equally applicable to a system compatible with NTSC. Section 4 explains how the principles may be applied to NTSC, and describes the results of computer simulations of such a system.

Appendix 1 contains off-screen photographs illustrating the performance of the PAL-compatible form of the algorithm, and Appendix 2 shows similar photographs for the NTSC case.

2. EXPLANATION OF THE CODING ALGORITHM

2.1 Description of the coded signal

The coded signal (Fig. 1) occupies a bandwidth of approximately 9 MHz and closely resembles a conventional PAL signal below about 5.5 MHz, as explained earlier. The junction between the luminance and chrominance signals around f_{sc} is formed using a coding method known as *phase- segregated* or *Weston Clean* PAL[1]. This method ensures that luminance and chrominance signals can be separated perfectly without the need for motion-adaption or sharp-cut filters to perform band segregation. The separable nature of the coding system is unaffected even if the bandwidth of the coded signal is restricted to approximately 5.5 MHz.

The signal carries additional chrominance information in the region between approximately 5.5 and 6.6 MHz, as explained earlier, allowing the system to convey chrominance signals with a bandwidth of approximately 2.2 MHz. Between approximately 6.6 and 8.8 MHz the signal carries additional high-frequency luminance information, giving a total luminance bandwidth of about 6.6 MHz. The junction between the chrominance signal and the additional luminance signal is created using sub-band synthesis techniques, allowing the signals to be separated perfectly in the decoder by sub-band analysis. This is in essence the same process as phase-segregated coding. Thus the entire spectrum of the signal is utilised fully, without the need for guard bands between different parts.

Fig. 2 *(page 4)* shows the two-dimensional spectra of the luminance and chrominance signals that the signal can convey, indicating the frequencies in the coded signal at which the various parts travel. These spectra are drawn to the same scale of horizontal and vertical resolution for a 16:9 display. The figure also

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* The actual figure is $2f_{sc}$ (8.8672375 MHz); the figure 8.8 MHz is used throughout to clarify the relationship with $f_{sc}/2$, f_{sc} and $3f_{sc}/2$; these quantities have the approximate values 2.2 MHz, 4.4 MHz and 6.6 MHz respectively. In practice, aliasing and post-filter response make the bandwidth of the analogue signal closer to 9.1 MHz (–6 dB).

** All vertical frequencies in the Report are expressed in terms of cycles per *active* picture height (c/aph), assuming that there are 576 active lines.

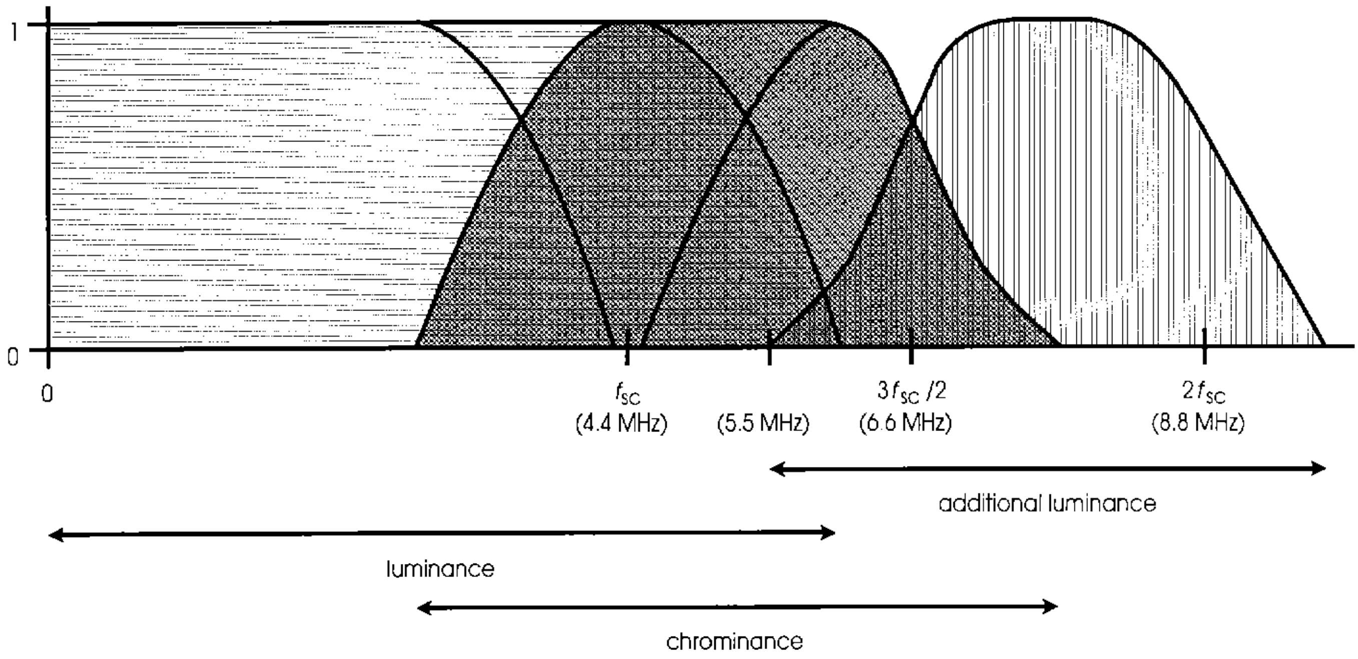

Fig. 1 - The spectrum of the coded signal

shows the vertical resolution limit for an 'interlaced Kell factor' of 0.65 (the effective maximum vertical resolution for an interlaced display). It can be seen that the horizontal and vertical resolutions of the system are well-matched to each other for this aspect ratio.

It should be noted that the highest frequencies in the coded signal (around 8.8 MHz) carry luminance detail with a horizontal frequency in the region of f_{sc} and vertical frequencies between 72 and 216 c/aph. These frequencies occupy the top part of the spectrum of the signal when it is sampled at $4f_{sc}$. If these frequencies are to be preserved, special consideration must be given to the pre- and post-filters used in the ADC and DAC circuitry of equipment operating at $4f_{sc}$ when the analogue interfaces of such equipment are used. Since the top part of the spectrum is unused in conventional PAL, filters in existing equipment are unlikely to have a suitable response. Further discussion of filter characteristics will be found in Section 2.2.5.

2.2 Description of the coding system

The operation of the coder can best be explained by separating it into two parts: firstly, pre-filters that take the incoming RGB signal and from it generate luminance and chrominance signals which may be sub-sampled in the required manner; and secondly, filters, samplers and modulators which form the coded signal from the sampled luminance and chrominance signals. Fig. 3 *(overleaf)* shows the pre-filters and Fig. 4 *(overleaf)* shows the circuitry for generating the coded signal. A decoder can similarly be divided into circuitry to recover the sampled-luminance and chrominance signals from the coded signal (Fig. 5, *(overleaf)* and interpolators to restore the sampled signals to their original form (Fig. 6 *(page 6)*). It is important that the filters used in the decoder to recover the sampled signals are very closely matched to the corresponding filters in the encoder, otherwise the system will not be free from cross-effects.

The following description concentrates on the coder; the operation of the decoder is not described in detail since its operation is the exact inverse of that of the coder.

2.2.1 Pre-filters

The pre-filters in a coder are shown in Fig. 3.

The luminance pre-filter in the coder is a horizontal low-pass filter which restricts the bandwidth of the luminance signal to $3f_{sc}/2$ (6.6 MHz) so that it can be sampled at a rate of $3f_{sc}$. The effective sampling lattice used resembles a form of f_{sc}, compressed horizontally by a factor of 3, and is discussed further in the following section. The lattice is not orthogonal; the repeat spectra from the sampling process are offset both vertically and temporally from the horizontal frequency axis. This is an advantage, since it allows the response of the pre-filter to extend right up to the theoretical maximum of $3f_{sc}/2$ (6.6 MHz) without the appearance of an objectionable static alias pattern, even if the filter is not very sharp. The non-orthogonality of the sampling lattice would allow a multi-dimensional pre-filter to be used. This would extend the horizontal bandwidth of the system beyond

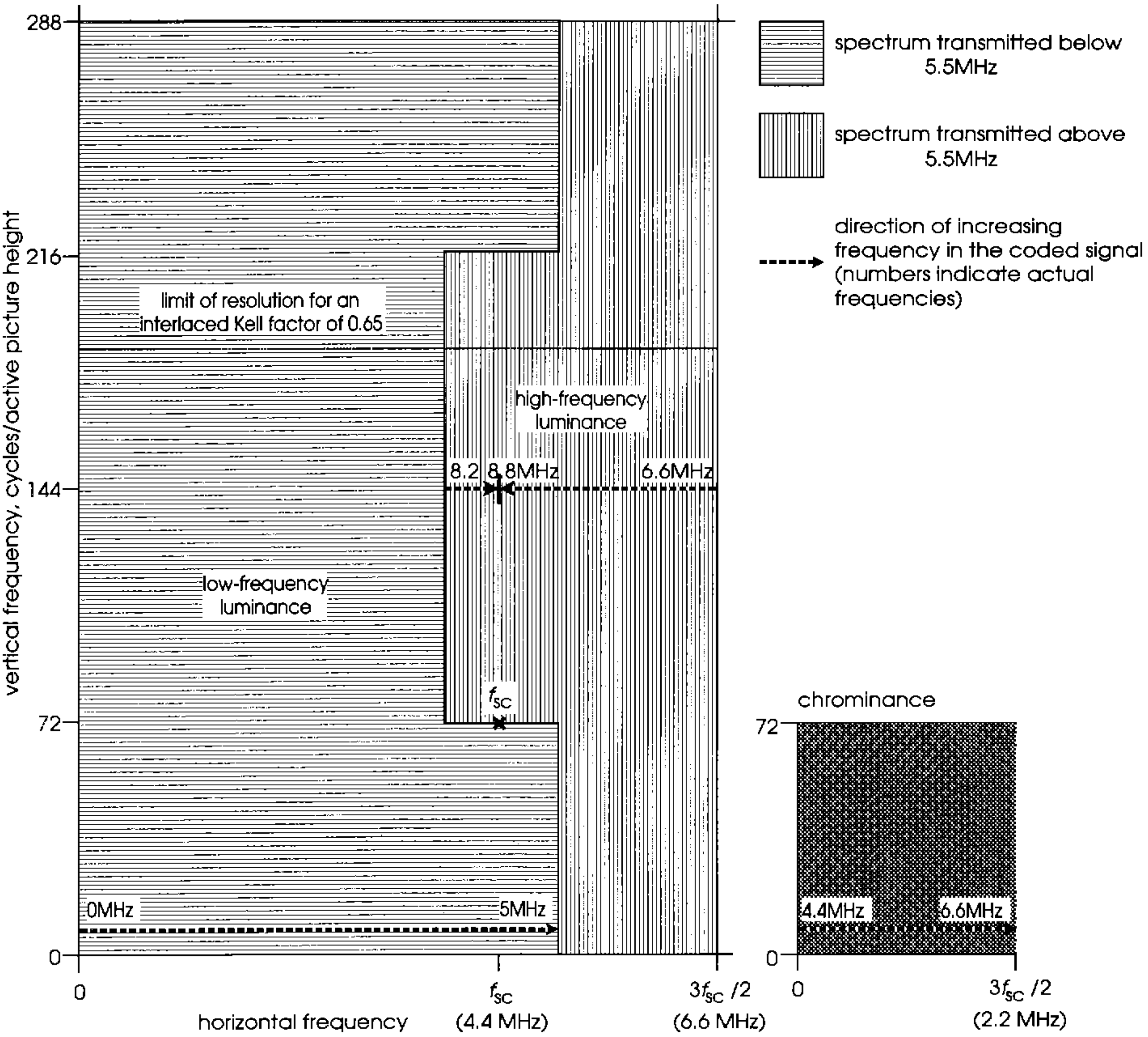

Fig. 2 - The two-dimensional spectra of the luminance and chrominance signals conveyed by the coding system, drawn for a 16:9 aspect ratio

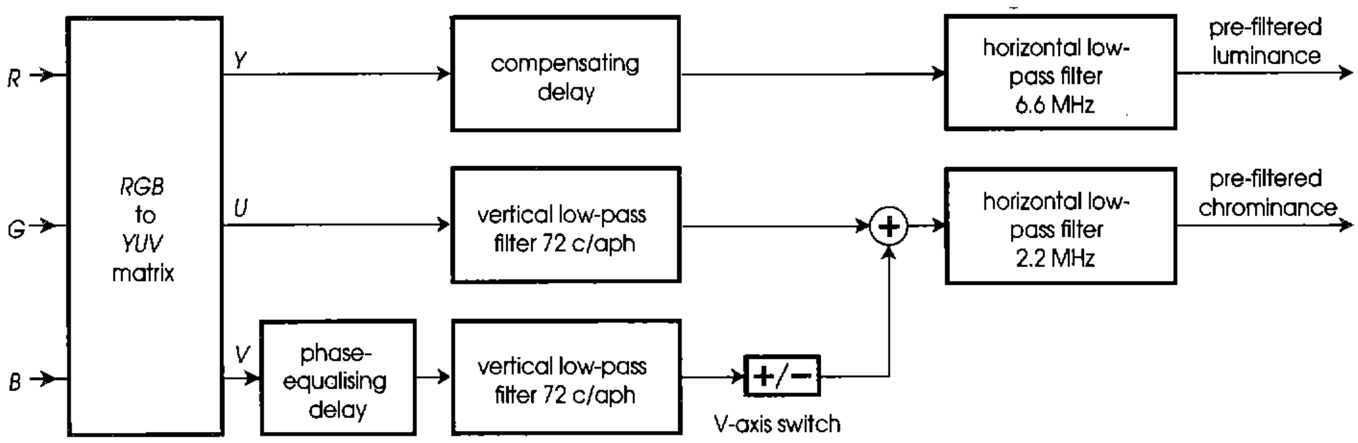
R
G
B
RGB to YUV matrix
Y
U
V
compensating delay
vertical low-pass filter 72 c/aph
phase-equalising delay
vertical low-pass filter 72 c/aph
+/−
V-axis switch
+
horizontal low-pass filter 6.6 MHz
horizontal low-pass filter 2.2 MHz
pre-filtered luminance
pre-filtered chrominance

Fig. 3 - Block diagram of pre-filters in a coder

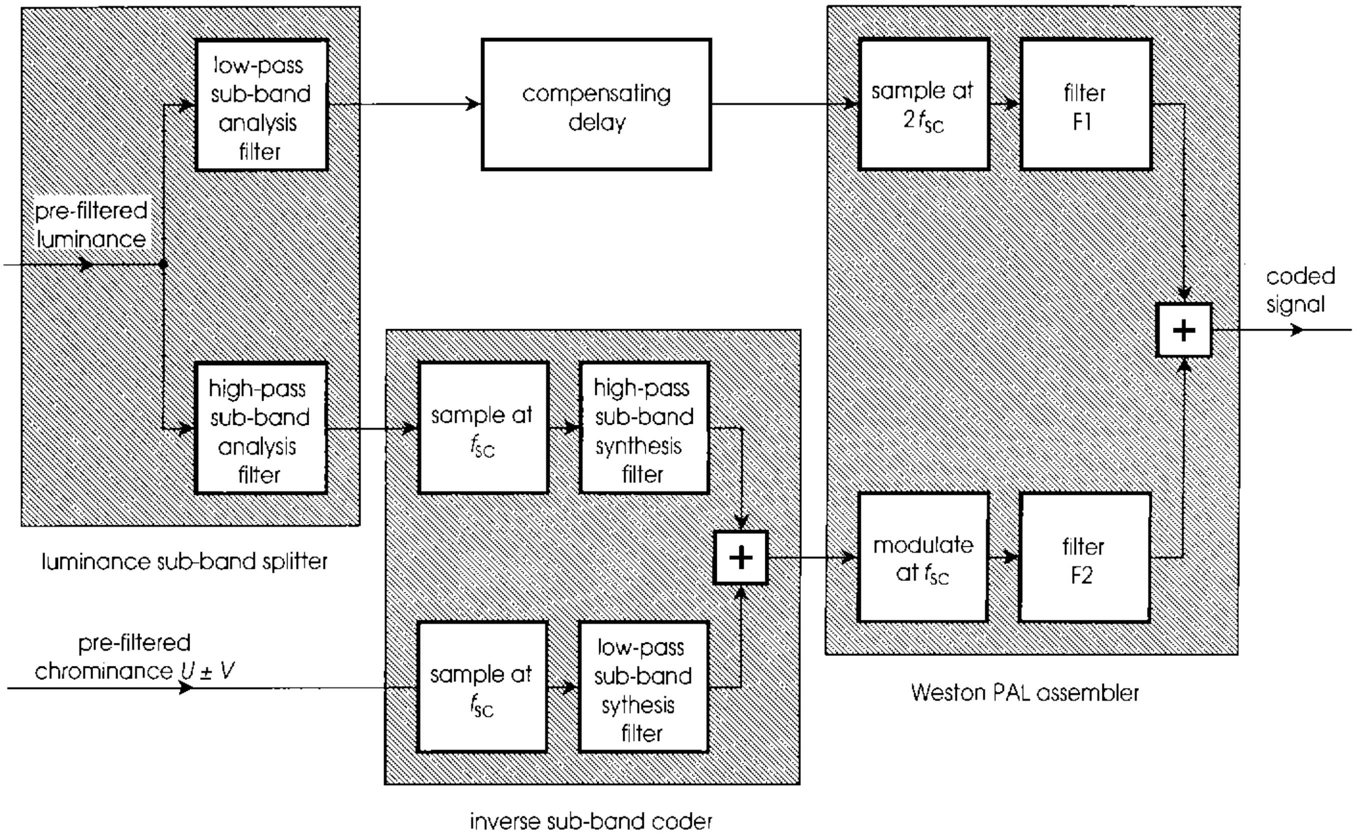
low-pass sub-band analysis filter
compensating delay
sample at $2f_{SC}$
filter F1
pre-filtered luminance
coded signal
+
high-pass sub-band analysis filter
sample at f_{SC}
high-pass sub-band synthesis filter
+
modulate at f_{SC}
filter F2
luminance sub-band splitter
pre-filtered chrominance $U \pm V$
sample at f_{SC}
low-pass sub-band sythesis filter
Weston PAL assembler
inverse sub-band coder

Fig. 4 - Block diagram of circuitry for forming the coded signal from the pre-filtered component signals

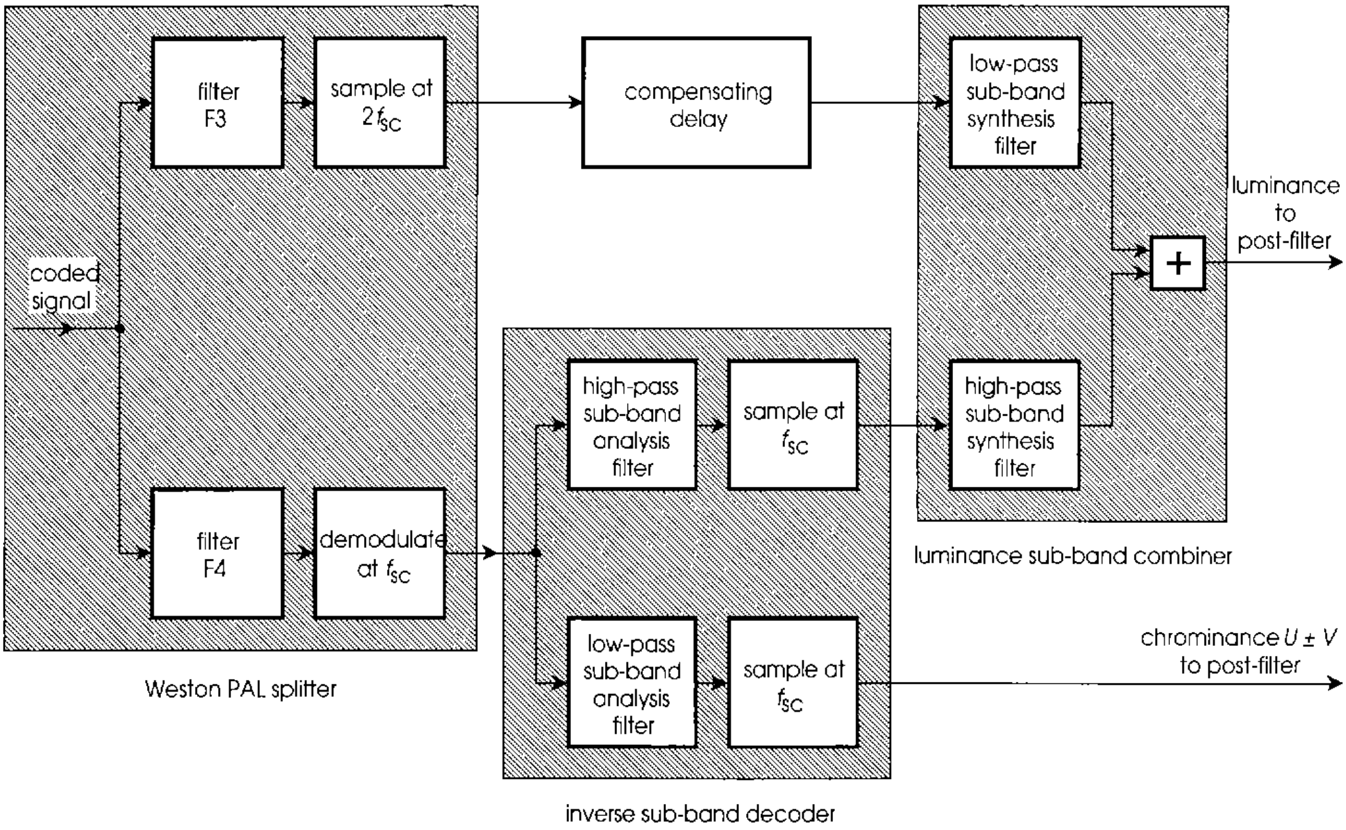
filter F3
sample at $2f_{SC}$
compensating delay
low-pass sub-band synthesis filter
luminance to post-filter
coded signal
+
high-pass sub-band analysis filter
sample at f_{SC}
high-pass sub-band synthesis filter
filter F4
demodulate at f_{SC}
luminance sub-band combiner
chrominance $U \pm V$ to post-filter
low-pass sub-band analysis filter
sample at f_{SC}
Weston PAL splitter
inverse sub-band decoder

Fig. 5 - Block diagram of the circuitry for splitting the coded signal into its component parts in the decoder

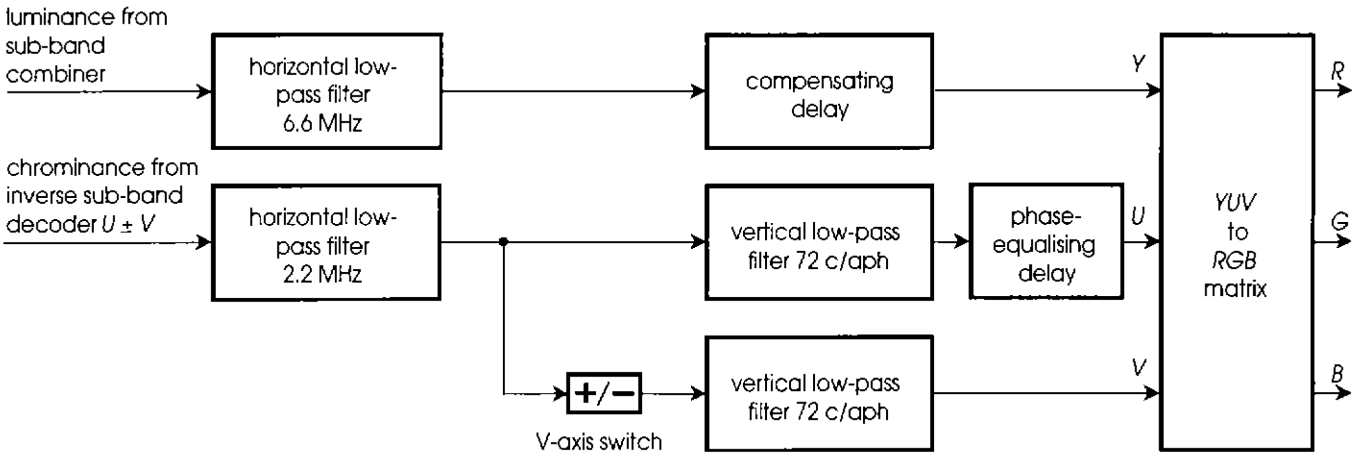
luminance from sub-band combiner
horizontal low-pass filter 6.6 MHz
compensating delay
Y
chrominance from inverse sub-band decoder U ± V
horizontal low-pass filter 2.2 MHz
vertical low-pass filter 72 c/aph
phase-equalising delay
U
+/−
V-axis switch
vertical low-pass filter 72 c/aph
V
YUV to RGB matrix
R
G
B

Fig. 6 - Block diagram of post-filters in a decoder

6.6 MHz in exchange for diagonal or temporal resolution; however, the extra sophistication that this would require was not considered to be justified.

The luminance post-filter in the decoder has essentially the same response as that of the pre-filter. It serves the purpose of removing alias signals at frequencies beyond $3f_{sc}/2$ caused by sub-sampling the high-frequency luminance sub-band, as described in the following section.

The Weston Clean PAL coding method involves vertical subsampling of the chrominance signals by a factor of two (the chrominance signals that are actually subsampled are on axes at 45° to *U* and *V*, i.e. *U*+*V* and *U*−*V*). Consequently, the *U* and *V* chrominance signals in the coder are pre-filtered vertically as well as horizontally. Therefore, the *U* and *V* signals are each vertically filtered within a field to remove frequencies above 72 c/aph. The filter is chosen to have a delay of an odd number of half-lines, to make the chrominance signal half a line late with respect to the luminance signal after the compensating delay. This allows for the fact that subsequent circuitry introduces a further one-line delay to the luminance but only half a line delay to the chrominance. A small horizontal delay is applied to the *V* signal with respect to the *U* signal in order to improve the registration of the signals when viewed using a conventional PAL decoder; this is explained further in Section 2.2.4.

The filtered *V* chrominance signal is then either added to or subtracted from *U* (according to the sign of the *V*-axis switch) to form a line-alternating chrominance signal of *U*±*V*. This places the *V* signal on a carrier centred at 144 c/aph. The signal can also be thought of as (*U*+*V*) sampled on, say, odd lines of a field, and (*U*−*V*) sampled on even lines. The signal is then low-pass filtered horizontally to approximately 2.2 MHz, giving the spectrum shown in Fig. 7. This

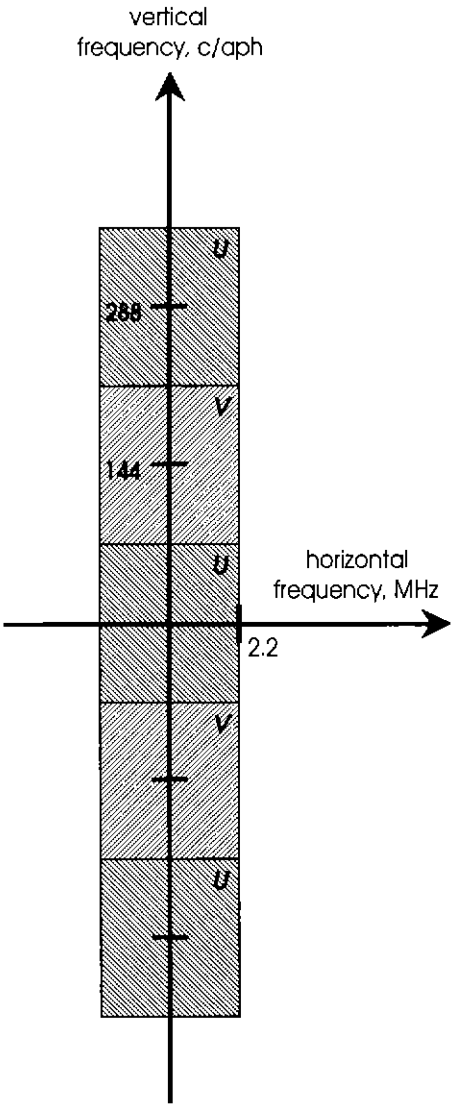

Fig. 7 - The spectrum of the band-limited chrominance signal

signal may then be sampled at f_{sc} on sites corresponding to positive peaks of the subcarrier. Since this sampling pattern is non-orthogonal, the comments made above regarding the luminance sampling pattern also apply to the chrominance.

The chrominance horizontal post-filter in the decoder (Fig. 6) removes the alias caused by sampling at f_{sc}, and has essentially the same response as the corresponding filter in the coder. The signal is then vertically low-pass filtered to yield the U component by removing the V component centred on 144 c/aph. To restore the V component, the signal is inverted on alternate lines according to the sign of the V-axis switch to produce the V signal with U modulated at 144 c/aph; a second low-pass filter then removes the modulated component. (This process is equivalent to using two low-pass vertical filters to interpolate the missing lines of $U+V$ and U-V, and then forming the sum to yield U and the difference to yield V).

2.2.2 Luminance splitter

Referring to Fig. 4, the pre-filtered luminance signal is split into low- and high-frequency parts using sub-band analysis filters. Sub-band filters are a well-known class of filter which allow a sampled signal to be filtered into two or more bands which may then be sub-sampled and subsequently up-sampled, post-filtered and summed, regenerating the original sampled signal. This is achieved in essence by arranging that the aliases from the subsampling processes exactly cancel losses in the filters[2]. Fig. 8 shows an example of a simple two-band analysis-synthesis network. In applications such as video coding it is common practice to use a lossy coding technique to code the samples of the higher frequency band; this is the main reason for splitting the signal. In the application described here, the signal is split into two because the chosen format of the coded signal does not allow all of the luminance bandwidth to be transmitted in a continuous part of the spectrum.

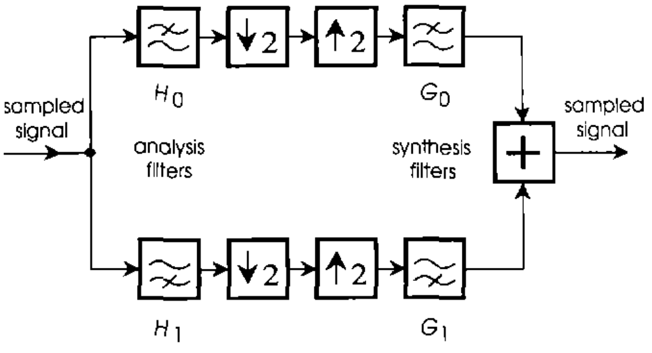

Fig. 8 - A two-band sub-band analysis-synthesis network

The filters used here are two-dimensional, splitting the signal as shown in Fig. 2. The reason for using a two-dimensional split is twofold:

1) The low-frequency part conveys a luminance signal having approximately isotropic resolution. Thus, if the high frequency part of the signal is lost by band-limiting the coded signal, the remaining available bandwidth is used in a near-optimal manner. This is of particular importance because the high-frequency luminance signal travels frequency-inverted in the coded signal, for reasons discussed later. Therefore, a loss of the highest frequencies in the coded signal will cause losses at the lower end of the high-frequency band. If a two-dimensional split were not used, this would cause the loss of frequencies above approximately 4.4 MHz for both low and high vertical frequencies; however, with the two-dimensional split of Fig. 2, only the higher vertical frequencies around 4.4 MHz are lost.

2) The shape of the low-pass filter closely matches the shape of the low-pass filter F1 used in the Weston PAL assembler, discussed later. Thus, the low-pass sub-band analysis filter and the filter F1 in the assembler form a matched pre- and post-filter pair, with a $2f_{sc}$ sampling operation between them. This ensures that all frequencies passed by the low-frequency sub-band analysis filter travel at the same frequency in the coded signal as they would in a conventional PAL signal. This guarantees good compatibility between the coded signal and conventional PAL. Indeed, the effect of the coding system resembles that of a 'line comb' PAL coder and decoder, although the luminance response is only 6 dB down at f_{sc}, whereas a conventional comb decoder would have a null at this frequency.

The output of the low-pass sub-band analysis filter is sampled at $2f_{sc}$ (which has a structure that is quincunxial within a field when the very small deviation from orthogonality of $4f_{sc}$ is ignored). The output of the high-pass sub-band analysis filter is sampled at f_{sc}, at sites corresponding to positive peaks of subcarrier. This lower sampling rate is allowable because of the band limitation applied to the signal by the pre-filter. Furthermore, the high-pass sub-band analysis filter is chosen to have a response very close to zero at frequencies below $f_{sc}/2$, since sampling at f_{sc} causes such energy to share the same spectrum as the wanted high-frequency luminance signal. This would cause cross-talk between high- and low-frequency luminance signals.

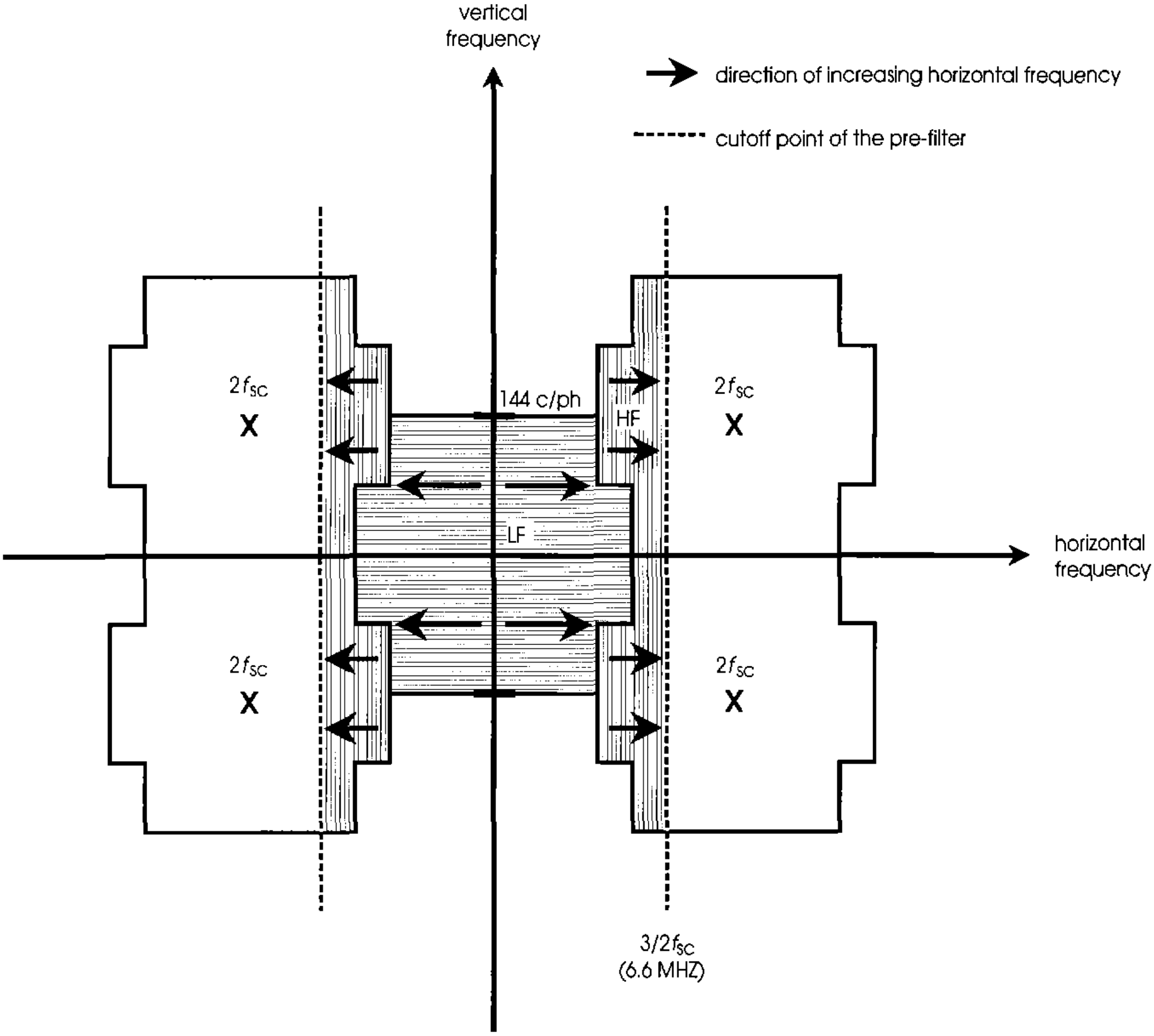

Fig. 9 - Pre-filtering and splitting the luminance spectrum

Fig. 9 shows the two-dimensional spectrum of the luminance signal, indicating the division into high and low-frequency parts and the effect of the pre-filter. The arrows show the direction of increasing horizontal frequency. Fig. 10 shows the high-frequency luminance signal after subsampling at f_{sc}. From this figure, it can be seen that the high frequency signal tessellates perfectly when sampled in this way. The arrows help to clarify which spectra have become inverted.

In the decoder circuitry shown in Fig. 5, the luminance signal is reconstructed from the sampled low- and high-frequency sub-bands using sub-band synthesis filters. Since the high-frequency sub-band has been sub-sampled by a factor of two, there will be an aliased signal present in the upper half of the high-frequency sub-band, which will appear as an alias in the upper quarter of the reconstructed signal at frequencies between $3f_{sc}/2$ and $2f_{sc}$. This alias is removed by the luminance horizontal post-filter, shown in Fig. 6, which was described above.

2.2.3 Combining chrominance and high-frequency luminance

Referring again to Fig. 4, the chrominance and high-frequency luminance signals, each sampled at f_{sc}, are then combined into a single signal sampled at $2f_{sc}$ prior to modulation at f_{sc}. The method used to combine these signals has been termed *inverse sub-band coding*. Sub-band coding, as explained above, is usually thought of as a way of allowing a single signal to be split into two signals, each sampled at half the rate of the original, in a manner that allows the original signal to be recovered perfectly. However, the method can equally be used to combine two independent sampled signals into one signal sampled at twice the rate, in such a way that the two signals

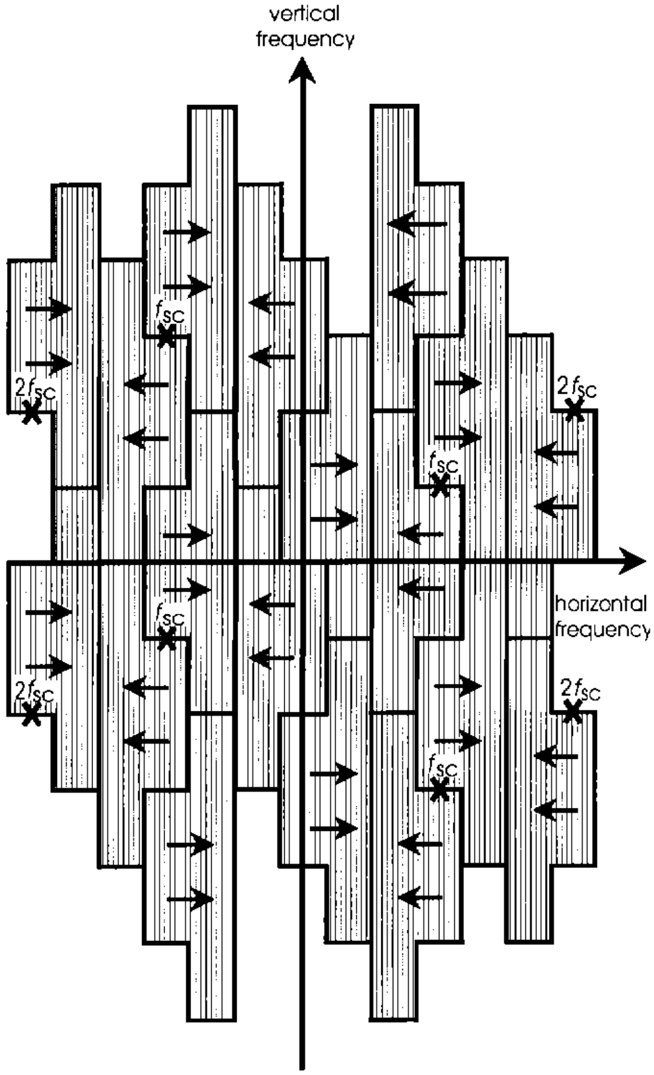

Fig.10 - The high-frequency luminance signal sampled at f_{SC}

(Arrows show direction of increasing horizontal frequency)

may be perfectly recovered without interaction or loss. This is achieved by up-sampling each signal by insertion of zero-valued samples and filtering using sub-band synthesis filters, in exactly the same way as a signal which has been previously split into two sub-bands is regenerated.

The process is most easily understood by considering the cascading of two perfect reconstruction sub-band networks of the type shown in Fig. 8. Since the sampled signal entering each of the two networks is the same (as they give perfect reconstruction), the signals in the low-frequency subsampled paths of each network must also be the same (and similarly for the high-frequency paths). Therefore, the synthesis part of the first network combines two signals in a way that allows the analysis part of the second network to separate them perfectly. Thus, an inverse sub-band coder is really no more than a sub-band decoder.

The combination of the chrominance and high-frequency luminance signals is therefore achieved by up-sampling the chrominance signal by a factor of 2, to a rate of $2f_{sc}$, and passing it through a low-pass sub-band synthesis filter. The high-frequency luminance signal is similarly processed with the corresponding high-pass filter (the up-samplers are not shown explicitly in Fig. 4). The filtered signals are added together, creating a signal sampled at $2f_{sc}$, with the chrominance signal occupying the lower half of the band and the luminance signal occupying the upper half. There will be some overlap between the two parts of the signal, because the filters will not be infinitely sharp, but this will not prevent perfect separation so long as the filters obey the normal rules for sub-band filters[2].

Fig. 11 *(overleaf)* shows the two-dimensional spectrum of the combined signal, ignoring the overlap. The horizontal region below $f_{sc}/2$ will be seen to be that from Fig. 7, and the region above this point will be seen to have come from the corresponding region in Fig. 10. The spectrum repeats beyond horizontal frequencies of f_{sc} since it is sampled at $2f_{sc}$; the figure shows part of the repeated spectrum in order to make the arrangement of the high-frequency luminance signal clear.

From Fig. 11, it can be seen that the high-frequency luminance signal is frequency-inverted in the combined signal: the arrows, that show the direction of increasing source signal frequency in the spectra, are pointing towards the origin in the area immediately adjacent to the chrominance band. Therefore, horizontal luminance frequencies just below $3f_{sc}/2$ in the original signal, travel at a frequency just above $3f_{sc}/2$ in the coded signal (just above the top of the chrominance band). Horizontal frequencies of f_{sc} whose vertical component is above 72 c/aph*, travel at a frequency of $2f_{sc}$ in the coded signal (at the top of the high-frequency luminance band). Frequencies whose vertical component is below 72 c/aph and whose horizontal component is below about 5 MHz, travel in the low- frequency luminance band, as explained in Section 2.2.2; thereby ensuring that these important frequencies are not lost if the upper part of the coded signal is attenuated.

The spectrum is inverted because that part of the spectrum of Fig. 10, which is conveyed by the high-pass sub-band synthesis filter, originates predominantly from the negative frequency part of a repeat spectrum centred on $2f_{sc}$; being created by subsampling the original high frequency luminance signal, shown in Fig. 9, at f_{sc}. Alternatively, we can think of the high frequency luminance spectrum as having been 'folded' by the sampling process.

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* The division into low vertical frequencies (which travel around f_{sc}) is gentle, since the luminance sub-band filters that are responsible for this split take contributions from only two field lines. To simplify the explanation, however, the text assumes a sharp division at 72 c/aph.

It is interesting to note, that it would be possible to re-invert the spectrum of the high luminance frequencies when forming the coded signal, so that the highest frequencies carry luminance information with a frequency around 6.6 MHz; such an arrangement would minimise the loss in picture quality associated with losses at high frequencies. However, this requires modulation of the high luminance frequencies by a frequency of $f_{sc}/2$, and the consequent provision of a corresponding reference signal at the decoder having the correct phase. This cannot be achieved in a normal studio environment, since attempts to obtain a phase reference, either by reference to the falling edge of syncs or by the insertion of a small reference burst in the signal, will not work if the signal is subjected to processes such as mixing and four-field editing. It was therefore decided to leave the high frequency luminance signal in its inverted form, obviating the need for such a phase reference.

Finally, the combined chrominance and high-frequency luminance signal, sampled at $2f_{sc}$, is modulated at f_{sc} as it enters the Weston PAL assembler, placing it in the correct part of the spectrum to resemble a PAL signal.

In the decoder, the chrominance and high-frequency luminance signals are separated by the use of sub-band analysis filters which match those used in the coder, as shown in Fig. 6. The filtered signals are re-sampled at f_{sc}, to yield sample values identical to the original signals in the coder.

2.2.4 Weston PAL assembler

Referring again to Fig. 4, the low-frequency luminance signal and the chrominance/high-frequency luminance signals, both sampled at $2f_{sc}$, are then combined into a single PAL-like signal sampled at $4f_{sc}$. This is accomplished by up-sampling each signal by a factor of two, to $4f_{sc}$, by inserting zeros and using the filters F1 and F2 in an arrangement termed a *Weston*, or *phase-segregated,* PAL assembler. The up-sampling is not shown explicitly in Fig. 4; indeed, the arrangement could be implemented with all data paths at $4f_{sc}$, so that no rate-changing is required. In such an implementation, the effect of the sampler and modulator is simply to multiply samples by +1, 0, or −1 in the appropriate pattern. The operation of the assembler has been well-documented elsewhere[1,3,4], so only a brief non-mathematical description will be given here.

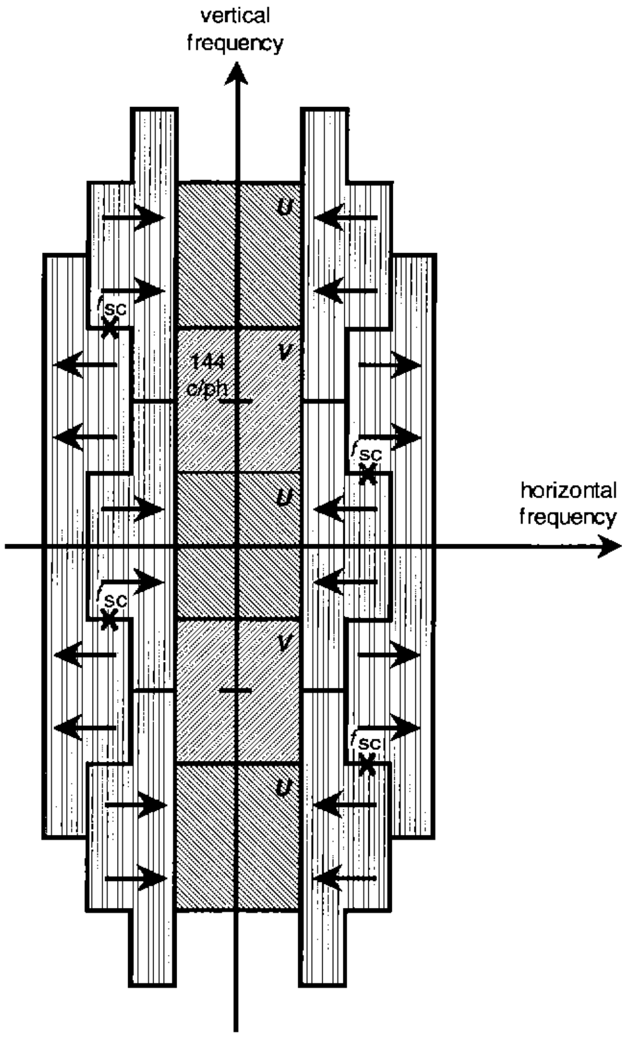


Fig. 11 - The chrominance signal combined with the high-frequency luminance signal before modulation at f_{sc}

The assembler can be considered as a special type of inverse sub-band coder, similar to that used to form the combined chrominance/high-frequency luminance signal described above. As in that application, its task is to form a sampled combined signal from two signals sampled at half the rate, in such a way that the two signals can be recovered without loss or interaction. The additional requirement here is that the combined signal should closely resemble a conventional PAL signal. This is achieved by using two-dimensional sub-band synthesis filters to form the combined signal, each filter taking contributions from two successive field lines. Excluding the subcarrier region, however, F1 may be thought of as a low-pass filter, and F2 as a high-pass filter.

The most important feature of these filters, from the point of view of forming a PAL-compatible signal, is that F2 must behave like a $(\frac{1}{2},-\frac{1}{2})$ vertical filter at f_{sc}. The response of F2 is similar to that of the high-pass luminance sub-band filter, shown in Fig. 2, although its pass-band extends up to $2f_{sc}$. From this figure it will be seen that f_{sc} is in the middle of the

Field line	Chrominance signal	f_{sc} modulation pattern				Signal at input F2				Output of F2 (ignoring scaling factor)			
1	U−V	0	+	0	−	0	+U−V	0	−U+V	+U+V	−U+V	−U−V	+U−V
2	U+V	−	0	+	0	−U−V	0	+U+V	0	+U+V	+U−V	−U−V	−U+V
3	U−V	0	−	0	+	0	−U+V	0	+U−V	−U−V	+U−V	+U+V	−U+V
4	U+V	+	0	−	0	+U+V	0	−U−V	0	−U−V	−U+V	+U+V	+U−V

transition region of the filter. This characteristic ensures that the line-alternating $U \pm V$ signal, modulated at f_{sc}, is converted to the conventional PAL form of U and switched V, modulated at f_{sc} on carriers at 45° to the sampling phase. This process is illustrated above (samples are on a $4f_{sc}$ lattice).

The coded signal resembles conventional PAL only in areas devoid of chrominance detail. Where the chrominance signals change vertically, the $(\frac{1}{2},-\frac{1}{2})$ filter will act on lines having differing chrominance values and the resulting signal will not appear to be exactly like PAL. Similarly, where there are significant horizontal chrominance frequencies present, regions of the filter passband that are away from f_{sc} will be explored; the vertical response of the filter F2 will then deviate from $(\frac{1}{2},-\frac{1}{2})$. When a conventional PAL decoder is used, these deviations can manifest themselves as slight mis-registration between Y, U and V, and the appearance of Hanover bars in the case of a simple PAL decoder. The mis-registration can be improved by delaying the V signal slightly with respect to U; this is the function of the phase-equalising delay in Fig. 3. The delay is of the order of a few samples at $4f_{sc}$; but the correction is not perfect because the required delay varies as a function of horizontal and vertical frequency. These deviations only affect the degree of compatibility with conventional PAL; they do not affect the ability of a matched decoder to yield a correctly-decoded signal as long as the filters satisfy the fundamental constraints applicable to all sub-band analysis and synthesis filters. The extra delay inserted is compensated for during decoding in such a matched decoder.

Fig. 12 *(overleaf)* shows the two-dimensional spectrum of the coded signal, simplified by omitting the overlap between the various parts of the signal. In particular, the vertical transition between the luminance and chrominance signals at f_{sc} is, in practice, very gentle, having the characteristic of a $(\frac{1}{2},-\frac{1}{2})$ filter. This gives rise to significant overlap in this region of the spectrum. The spectrum is shown covering horizontal frequencies from $-2f_{sc}$ to $+2f_{sc}$, being the bandwidth of the final signal.

Fig. 13 *(page 13)* shows photographs of the signal spectrum, measured on a spectrum analyser, as well as contributions from the various parts of the signal. The spectrum of the complete signal can be considered as the projection of Fig. 12 along the horizontal axis. For comparison, the figure also shows a conventional PAL signal and its constituent parts. It can be seen that the spectra of the two signals are similar; the main differences are the high-frequency luminance signal in the region 7-9 MHz and the shape of the chrominance signal, which has a smaller lower sideband and an extended upper sideband compared with conventional PAL.

PAL syncs and burst are then added to the output of the assembler before conversion to an analogue signal (these stages are not shown in Fig. 4).

In the decoder, shown in Fig. 5, the splitter filters F3 and F4 act as sub-band analysis filters that match the synthesis filters F1 and F2. The output of F3 is sampled at $2f_{sc}$ to yield nominally identical sample values to those entering F1. The output of F4 is demodulated at f_{sc} (a process which is equivalent to sampling at $2f_{sc}$ and inverting alternate samples); this yields sample values nominally identical to those entering the modulator prior to F2.

2.2.5 DAC filter

The signal generated by the assembler is a sampled signal (assumed to be at a rate of $4f_{sc}$) containing frequencies in the range 0-$2f_{sc}$; it must be converted into analogue form in such a way that when it is subsequently digitised in a decoder, or other equipment operating at $4f_{sc}$, sample values as close as possible to the original $4f_{sc}$ sample values are obtained. This is important, because it is desirable to minimise any losses to the signal. If the signal represented a conventional PAL or analogue component signal, a small degree of loss at frequencies near the top of the band would be of little consequence. However, for the signal described here, frequencies near $2f_{sc}$ carry luminance information from frequencies immediately above and below f_{sc} with vertical frequencies above 72 c/aph (see Figs. 2 and 12); as these frequencies are within the passband rather than on the edge, it is important to retain them wherever possible.

Therefore the DAC post-filter must be chosen in conjunction with the characteristic of the ADC pre-filter in the decoder to yield a filter product that is approximately Nyquist (skew-symmetric about a response of $(\frac{1}{2})$ at $2f_{sc}$). This ensures that samples

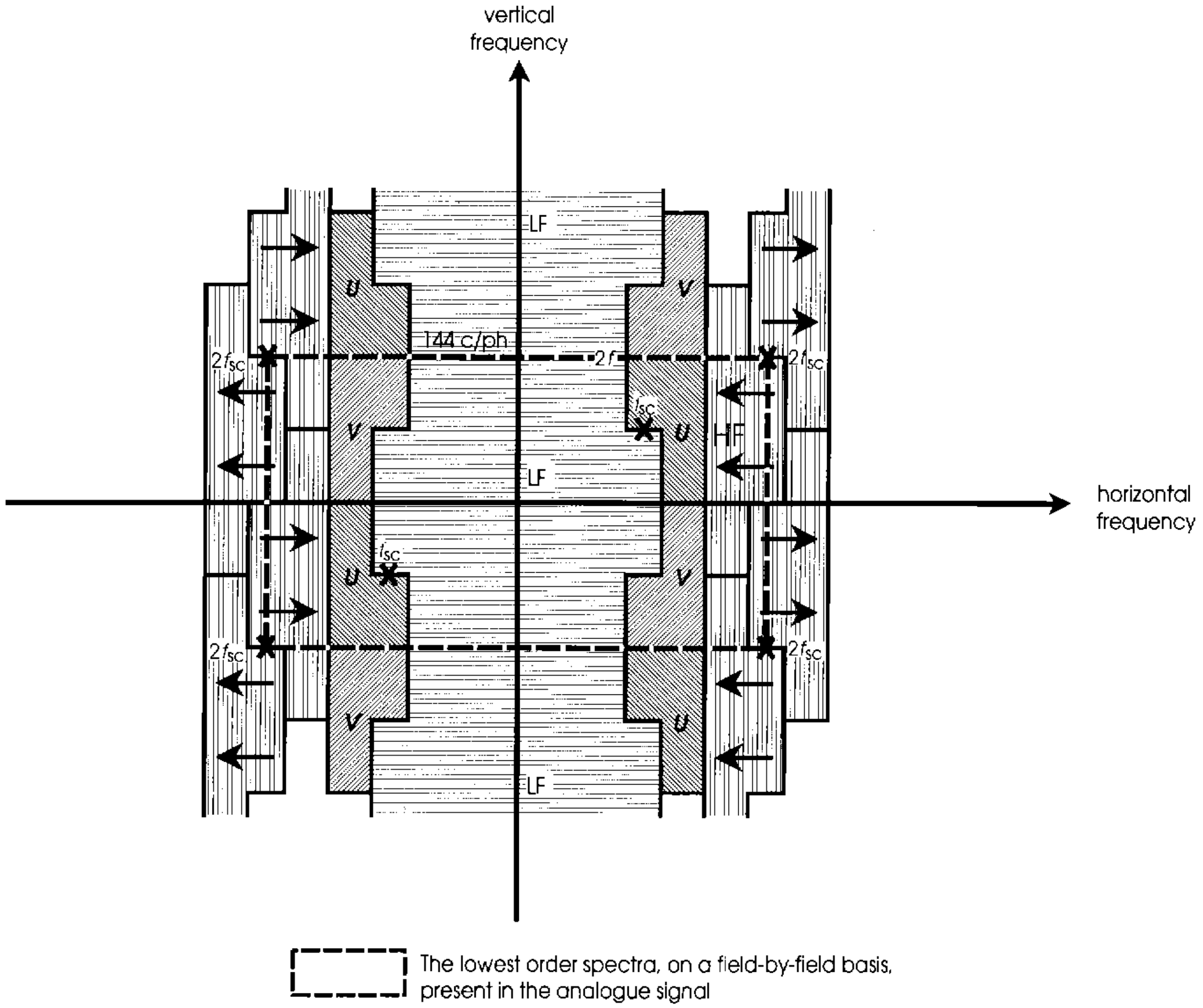


Fig. 12 - Simplified two-dimensional spectrum of the coded signal

with values very close to the original values are obtained when the signal is re-sampled in the same phase in the ADC. The choice was made to split the Nyquist filter equally between the DAC and ADC, each filter having a response approximately 3 dB down at $2f_{sc}$. Such filters are termed *root-Nyquist* or *half-Nyquist*. Analogue filters designed to this specification were tested using the experimental coder and decoder[5]. Very little visible difference was then observed between the decoded picture when either an analogue connection or a digital connection was made between the coder and decoder. This was true even when a zone plate test pattern was used, despite the fact that the filter product was only approximately Nyquist.

An alternative way of achieving the required response without the need for precision analogue filters is to over-sample the signal to, say, $8f_{sc}$, and use a digital filter with a half-Nyquist response before conversion to analogue. A similar approach may be used for the ADC. However, it has not been found necessary to use this more sophisticated approach, since analogue filters with acceptable performance are readily available.

For interfacing with other equipment operating at a sample rate of $4f_{sc}$, such as D2 and D3 recorders, it is possible to use the digital output of the coder directly. Experiments have shown that the D3 recorder is transparent to data when interfaced in this way. However, if analogue signals are to be used for such interfacing, then it is worth modifying the analogue pre- and post-filters in the equipment to match the chosen half-Nyquist response. It has been found that the post-filter in a D3 recorder gives about 9 dB of attenuation at $2f_{sc}$ and that the pre-filter gives somewhat more; consequently, the combined effects of these filters is to introduce a significant loss to luminance frequencies, together with an alias pattern, immediately around a horizontal frequency of f_{sc} at vertical frequencies in the region of 72 c/aph and

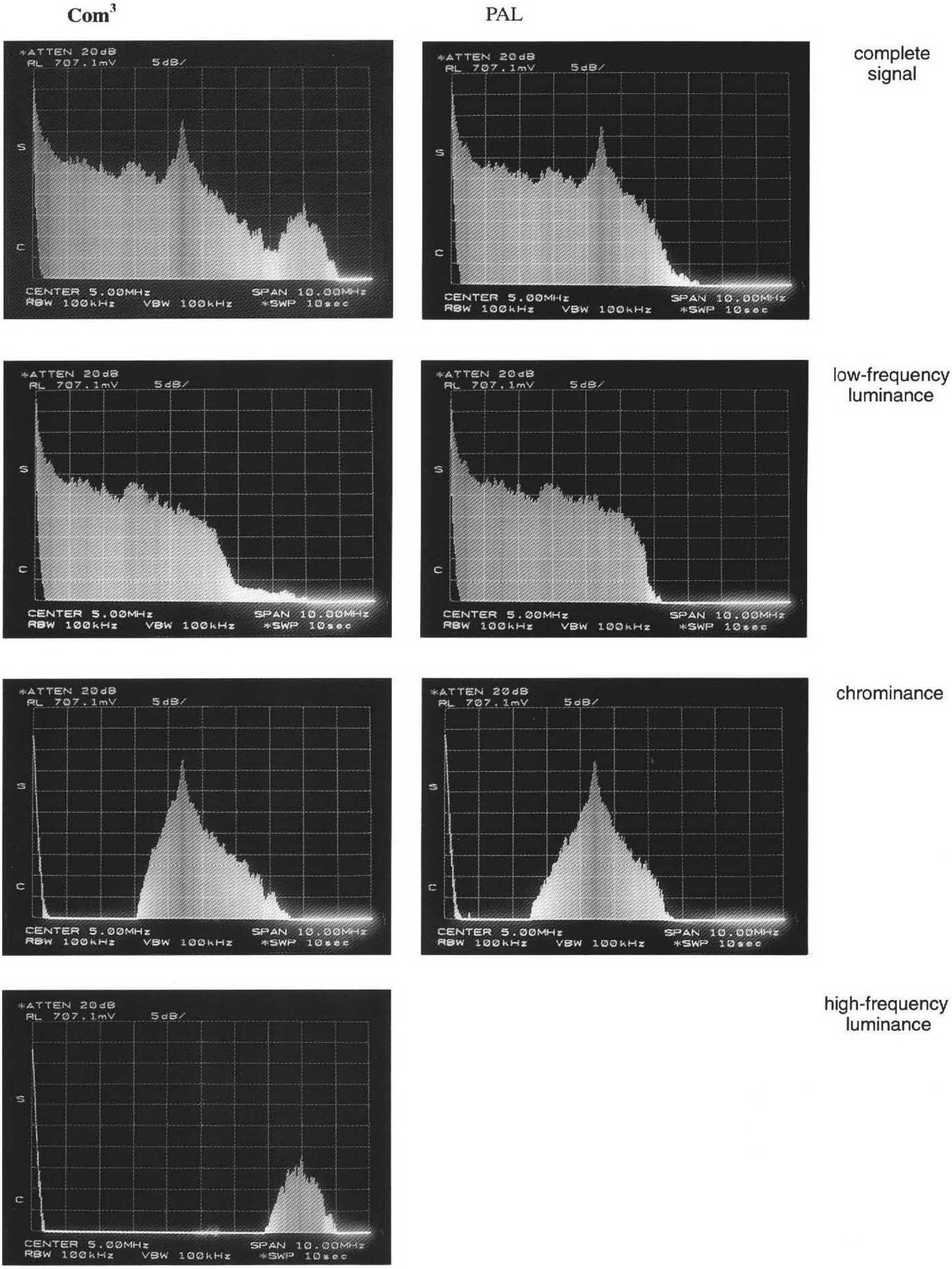


Fig. 13 - Measured spectra of the coded signal and conventional PAL.

greater. Although such effects may not be readily apparent on the majority of real pictures, it is clearly desirable to eliminate them wherever possible, particularly as the effects will accumulate with successive generations of recording. Modifying the pre-filter is most important, since it causes the greatest loss.

3. FIELD TRIALS

This section gives a brief summary of field trials that were carried out to test the ability of existing composite studios to carry the coded signal. A brief description of the experimental coder and decoder that were used is also given. Further details of the codec and the field trials can be found in another Report[5].

3.1 Experimental codec

The development, demonstration and testing of the coding algorithm were aided by the construction of an experimental coder and decoder, shown in Fig. 14. These are composed largely of general-purpose digital filter circuit boards which use VLSI digital filter ICs operating at a sampling frequency of $4f_{sc}$. The filter coefficients are programmable from a personal computer, so that new filters can be evaluated on a range of picture material without the need for time-consuming software simulation. Although the experimental coder and decoder together occupy most of a studio equipment bay, in practice it is possible to implement each in a box the size of an existing high quality studio PAL coder or decoder, by designing dedicated circuit boards.

3.2 Tests in existing studios

Preliminary field trials have been carried out in Studio 7 at the BBC's Television Centre (in London) in order to determine the extent to which the coded signal is compatible with existing PAL studio equipment; also, to observe what changes, if any, would be required to signal routeing and working practices. This studio is one of the older studios in terms of the majority of installed equipment, although the vision mixer (a Grass Valley GVG 200) is relatively new. Further tests were also carried out in a 'Type 5' outside broadcast vehicle and at the studios of Channel 4 in London, the latter under the auspices of the Eureka 637 project ('PALplus').

Using the experimental hardware, component signals from a stills store and from a camera were coded and then passed through devices in the normal studio signal chain, including the vision mixer, processing amplifier, delay lines and distribution amplifiers. The decoded picture was compared with the 'ideal case' where the coder and decoder were digitally connected together back-to-back. The observed degradation of the signal caused by the studio chain was very small, and was only visible in a zone plate test pattern, with slight losses and aliasing at frequencies around a horizontal frequency of f_{sc} and above 72 c/aph vertically. Most of the degradation was traced to the processing amplifier, which introduced losses above about 8 MHz. Tie-lines to another part of Television Centre (the Central Apparatus Room) were found to have no noticeable effect on picture quality.

Some measurements were made of the gain and group delay characteristics of typical modern equipment and signal paths in other parts of Television

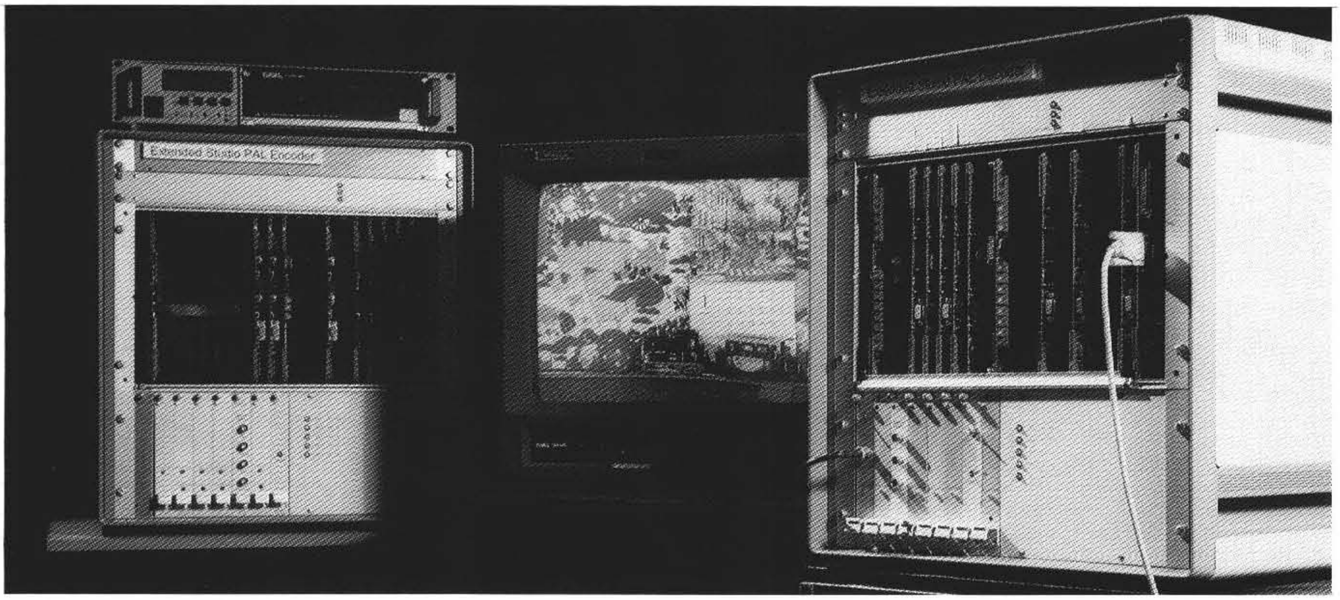


Fig. 14 - The experimental coder and decoder.

Centre, to see whether other areas could possibly present problems. These measurements showed that the majority of signal paths (including mixers, switching matrices, distribution amplifiers and tie lines) were less than 1 dB down at $2f_{sc}$ and had a group delay at this frequency within 20 ns of its value at f_{sc}. The worst figures were a loss of 2 dB and a relative delay of 30 ns at $2f_{sc}$.

Since the coding system is linear, any losses at $2f_{sc}$ equate directly to the amount of loss centred on a horizontal frequency of f_{sc} and a vertical frequency of 144 c/aph in the decoded luminance signal. The effect of group-delay variations between DC and f_{sc} is small and comparable to that for conventional PAL; signal paths can be expected to perform well over these frequencies anyway. Group-delay variations between f_{sc} and $2f_{sc}$ cause mis-registration between low- and high-frequency luminance signals (preventing perfect alias cancellation) and slight crosstalk between chrominance and high-frequency luminance. Computer simulations showed that delays of around 25 ns between f_{sc} and $2f_{sc}$ caused very slight aliasing but negligible cross-effects on a zoneplate, with no visible effect at all on any of the test sequences used. A delay of 60 ns resulted in more severe aliasing and about 8 dB of signal loss around a horizontal frequency of f_{sc} and a vertical frequency of 144 c/aph, although even this was barely visible on critical picture material, appearing as slight diagonal ringing. Therefore, no significant impairments would be expected from the group delay values encountered. The degree of losses and aliasing seen on zoneplate signals, based on measurements made in Studio 7, are thus consistent with that expected of typical studio equipment.

Compatibility with conventional PAL was assessed by wiping and mixing with conventional PAL signals, and viewing the results using a conventional PAL monitor alongside an *RGB* monitor fed from the **Com^3** decoder. Those parts of the picture coded with conventional PAL (including coloured wipe edges generated in the mixer) were found to have a quality very similar to conventional PAL when decoded using the new decoder. Under some circumstances, slight mis-registration between the luminance and the colour difference signals was visible, for the reasons explained in Section 2.2.4. There was also a reduction in fine cross-colour, resulting in a clean horizontal luminance response to about 5 MHz. Cross-luminance appeared on vertical chrominance transitions but was virtually absent on horizontal transitions, unlike conventional PAL where cross-luminance appears only on horizontal chrominance transitions.

When decoding the signal using a conventional PAL decoder, a picture quality similar to conventional PAL was observed. Some *U/V* crosstalk was apparent on vertical chrominance transitions, although this was less apparent when a line-delay (as distinct from simple) PAL decoder was used. Coarse cross-colour was removed, resulting in a subjective improvement in picture quality for scenes containing significant amounts of high-frequency luminance. Further details of the compatibility aspects of Weston PAL coding can be found in Ref. 1.

Luminance keying and chroma-keying were also tried. Keying between conventional PAL and **Com^3** gave a picture quality at key boundaries similar to that obtained when keying between two conventional PAL signals, and chroma-keying between two **Com^3** signals gave no noticeable picture degradation. The chroma-key tests were performed with a key derived from the original *RGB* signal, which is normal studio practice; although a further experiment showed that it was possible to derive a key signal from the **Com^3** signal and achieve results significantly better than could be obtained using a key derived from conventional PAL, but not as good as from the original *RGB*.

Other tests examined the use of equipment that acted essentially as a 5.5 MHz low-pass filter. The items tested included a synchroniser (which used a $3f_{sc}$ sampling frequency), a 'C' format analogue recorder and a BT analogue line between London and Scotland. The decoded picture was found to be band-limited to the region shown in Fig. 2 as expected; some alias patterning was visible at luminance frequencies around the edge of the passband. The complete freedom from cross-effects remained. One other effect that was noted was the appearance of ringing on horizontal chrominance transitions; the rings appeared to be of a larger amplitude than those appearing when a conventional PAL signal was subjected to the same processing. This effect was thought to be due to the single side-band nature of the chrominance signal in the **Com^3** system. The presence of a lower chrominance side-band in conventional PAL prevents a low-pass filter from removing all chrominance information above the cutoff frequency of the filter, resulting in a more gentle roll-off characteristic. However, on all available test material, the band-limited decoded **Com^3** signal gave a picture quality superior to that of conventional PAL; principally, by virtue of its freedom from cross-effects.

A PAL synchroniser, which decoded into components and re-coded to composite at the output, was also tested. This introduced PAL cross-effects and reduced resolution. Other equipment incorporating conventional PAL decoders and coders (such as digital video effects units) would be expected to introduce similar effects. Such equipment could, of course, be re-equipped with **Com**^{3} coders and decoders, thereby limiting any loss in quality to that from one cascaded decode/code process (discussed in the following paragraph).

An experiment was tried in which coding and decoding processes were cascaded four times, using a D1 component digital recorder to record intermediate generations. The coder and decoder were connected together using a direct analogue connection. Each generation introduced a slight reduction in vertical chrominance resolution, due to losses in the vertical chrominance pre- and post-filter. A small reduction of horizontal chrominance resolution was also apparent. Luminance resolution remained essentially unchanged; although a faint moving alias pattern around a horizontal frequency of f_{sc} and a vertical frequency of 72 c/aph began to appear in later generations, due to accumulating losses in the analogue PAL pre- and post- filters in the coder and decoder. No cross-effects were introduced.

The effect of multiple-generation recording using an analogue interface was investigated. Two D3 recorders were equipped with new pre- and post-filters of the type described in Section 2.2.5. They were connected together back-to-back and up to six generations of recordings of test patterns and critical moving material coded with **Com**^{3} were made. The tapes were then replayed into a decoder and the picture quality observed. Successive generations introduced alias patterning of the type described in the previous paragraph, together with a slight gain error in the same region of frequency space (due to the product of the responses of the analogue pre- and post-filters not being perfectly 'Nyquist'). Slight phase errors, which accumulated during the recordings (resulting from imperfect alignment of the recorders), gave rise to low-level cross-effects:

- Overall errors of the order of 2° produced small amounts of cross-colour, just visible on a zone-plate at high diagonal frequencies.
- Errors of the order of 4° generated cross-luminance that was just visible on some kinds of picture material.

A reliable way of determining when the phase error was zero was to examine the decoded Y or G signal from colour bars using a waveform monitor. Any small amounts of cross-luminance were then clearly visible, appearing as low-level noise in saturated areas. The phase could then be adjusted to give zero cross- luminance.

The field trials showed that the coding system performs better than conventional PAL in all respects other than vertical chrominance resolution. Although, as stated earlier, the chrominance response is better matched to the available bandwidth than that of conventional PAL, the tests at Television Centre suggested that the reduced vertical chrominance response may initially be of some concern to studio engineers.

One other practical aspect of the implementation of the coding system in the studio relates to signal timing: the coder and decoder each introduce several lines of delay. This will require component sources to produce advanced outputs, if the coders in the studio are to be co-timed with existing genlocked conventional PAL equipment. This could be achieved with a feed of early syncs to component sources.

4. APPLICATION TO NTSC

Although this Report has concentrated on a PAL-compatible system, the principles are equally applicable to NTSC. This Section outlines how an NTSC-compatible system can be realised, and discusses the results of computer simulations of such a system.

Section 4.1 considers the differences between the subcarrier structures of PAL and NTSC, and the consequences for the operation of the **Com**^{3} system, including the need for a perturbed subcarrier structure. Section 4.2 considers the differences in the chrominance processing between the systems, which include the use of I and Q chrominance components instead of U and V, and a different vertical chrominance switching action. Section 4.3 compares the performance characteristics of the PAL- and NTSC-compatible systems, and Section 4.4 discusses the results of computer simulations.

4.1 Subcarrier structure

From the perspective of the operation of the assembler and splitter, the major difference between PAL and NTSC is that the PAL f_{sc} modulation pattern retards by 90° per line whereas the NTSC f_{sc} modulation pattern retards by 180° per line. That is, for NTSC, $2f_{sc}$ is an exact multiple of line frequency and therefore $2f_{sc}$ is orthogonal, whereas for PAL, $2f_{sc}$ is approximately an odd multiple of half the line frequency, and therefore $2f_{sc}$ is quincunxial.

Now, because the assembler and splitter filters are two-dimensional, the sampling operations must be quincunxial, to enable the filters to operate as sub-band filters. (Note, that a quincunxial pattern is the only one which can support 2:1 subsampling when the band-split is other than purely horizontal or vertical.) Therefore, the sampling structure used by the assembler and splitter must have a 180° phase shift per line.

Therefore it is necessary to perturb the NTSC $2f_{sc}$ sampling pattern to yield a quincunxial pattern[6]. This perturbed structure will be referred to as $2f_{sc}$*. The perturbation of the $2f_{sc}$ structure results in a corresponding perturbation of the f_{sc} structure used to modulate the chrominance signal; this perturbed NTSC subcarrier will be referred to as f_{sc}*. Since the $2f_{sc}$* structure has a 180° phase shift per line, the f_{sc}* modulation pattern will correspondingly have a 90° phase shift per line, like PAL subcarrier. The average frequency of the perturbed carrier is that of the NTSC subcarrier, approximately 3.58 MHz.

The field-to-field nature of the perturbation may in principle be chosen freely, since it is only the line-to-line nature which determines the correct operation of the assembler and splitter (since they have no memory beyond two lines). Indeed, it is even possible to use a form of f_{sc}* resembling the PAL 8-field structure to yield an NTSC signal! However, there are several criteria that the coded signal must satisfy which limit the choice of perturbed sampling structure:

- The coded signal must have a four-field sequence, since there is no synchronisation information in a standard NTSC signal to allow a decoder to be locked to a longer sequence.
- The relationship between field 1 and field 3 of the four-field sequence of f_{sc}* should be the same as that between fields 1 and 3 in NTSC f_{sc} (a phase shift of 180°) in order to allow the use of processes such as two-field editing. Such processes convert a 'field 1' to a 'field 3' by shifting the coded signal by half a subcarrier cycle. The same applies to fields 2 and 4.

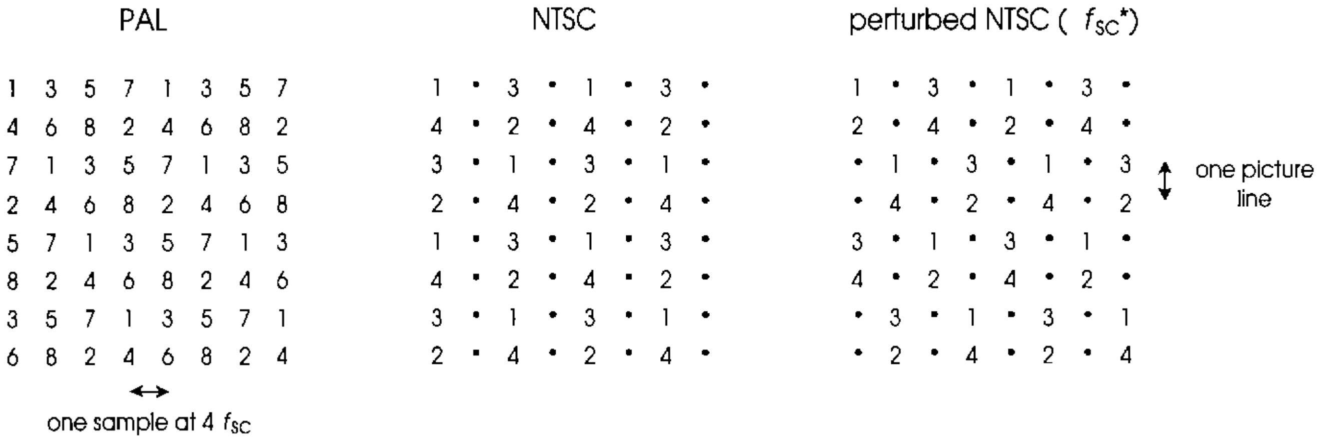
When these constraints are taken into account, the choice of possible modulation patterns is limited. There are two choices for the pattern in field 1, these having a line-to-line phase shift of +90° or –90°. This choice is arbitrary. The pattern in field 2 may be chosen independently to be either of these two patterns; this choice affects the pattern of aliases at the luminance and chrominance band edges and is discussed in more detail below. Additionally, the pattern in field 2 may be positioned in any one of four possible spatial relationships with respect to the pattern in field 1 (samples on adjacent picture lines either aligned vertically or offset by 1, 2 or 3 samples at $4f_{sc}$). The choice of spatial relationship has no material effect on the performance of the system since it merely changes the absolute phase of alias patterns. Once the patterns in fields 1 and 2 are chosen, the patterns in fields 3 and 4 are determined as explained above. Clearly, the same modulation pattern must be used in both coder and decoder.

Therefore, the only significant choice that has to be made is whether the modulation patterns in fields 1 and 2 are the same (each either advancing or retarding by 90° per line) or are different (one advancing by 90° whilst the other retards). The only aspect of the system performance materially affected by this choice is the alias pattern at the horizontal band edges (at frequencies around $3f_{sc}/2$ for luminance and $f_{sc}/2$ for chrominance), since both the chrominance and high-frequency luminance signals are subsampled on a lattice of f_{sc}*. If the modulation patterns are the same for both fields, alias patterns always appear in the same quadrant of horizontal-vertical frequency space, whereas if they are different the aliases alternate between the first and fourth quadrant on successive fields. The degree of compatibility with normal NTSC is unaffected by the choice.

An option was taken to use the pattern in which the modulation phase retards by 90° per line on odd fields (like PAL), but advances by 90° on even fields. The visibility of the alternating alias patterns produced by this arrangement was judged to be slightly lower than that of a non-alternating pattern. This choice means that the performance of the system is identical for lines sloping at a given angle, regardless of whether the slope is to the left or right. It should be noted, however, that the visibility of the alias patterns is generally very low for either case, since they are confined to the luminance- and chrominance-band edges.

An example of such a structure is shown in Fig. 15 *(overleaf)*. The structures of PAL and NTSC are also shown for comparison. All number '1's in the perturbed NTSC pattern will be seen to lie in the same pattern as those in the PAL structure. The pattern in field 2 will be seen to be the mirror image of that on field 1, with samples on a given line displaced by one $4f_{sc}$ sample to the left of the samples on the preceding line of the same field. The horizontal position of samples in field 2 relative to those in field 1 is arbitrary as explained earlier. The pattern in field 3 is the same as that in field 1 but horizontally displaced by two samples, giving the required phase shift of 180° per frame. Field 4 is similarly related to field 2 by a shift of two samples.

One consequence of having f_{sc}* change phase by 180° from frame to frame is that $2f_{sc}$* is then a frame-repetitive pattern. Thus, any alias patterns



PAL

1	3	5	7	1	3	5	7
4	6	8	2	4	6	8	2
7	1	3	5	7	1	3	5
2	4	6	8	2	4	6	8
5	7	1	3	5	7	1	3
8	2	4	6	8	2	4	6
3	5	7	1	3	5	7	1
6	8	2	4	6	8	2	4

NTSC

1	•	3	•	1	•	3	•
4	•	2	•	4	•	2	•
3	•	1	•	3	•	1	•
2	•	4	•	2	•	4	•
1	•	3	•	1	•	3	•
4	•	2	•	4	•	2	•
3	•	1	•	3	•	1	•
2	•	4	•	2	•	4	•

perturbed NTSC (f_{SC}^*)

1	•	3	•	1	•	3	•
2	•	4	•	2	•	4	•
•	1	•	3	•	1	•	3
•	4	•	2	•	4	•	2
3	•	1	•	3	•	1	•
4	•	2	•	4	•	2	•
•	3	•	1	•	3	•	1
•	2	•	4	•	2	•	4

Fig. 15 - Sampling structures for subcarrier of PAL, NTSC and perturbed NTSC (Numbers indicate the field in the 4- or 8-field sequence in which the sample falls on a positive peak of the subcarrier)

caused by sampling at $2f_{sc}^*$ appear static, unlike those in the PAL-compatible system, which move. The alias pattern is visible for high vertical luminance frequencies around f_{sc} in the picture produced when using a normal NTSC decoder; however, it is only apparent in the picture from a matching decoder when the coded signal has undergone a bandwidth limitation (it appears in the same frequency range). Although a moving pattern might be considered preferable under many circumstances, the static pattern has one advantage when a normal NTSC decoder is used: it gives rise to cross-colour which moves in such a way as to appear less visible than that from either a normal NTSC coder or from a variant of the coding system using a non- frame-repetitive $2f_{sc}^*$ pattern.

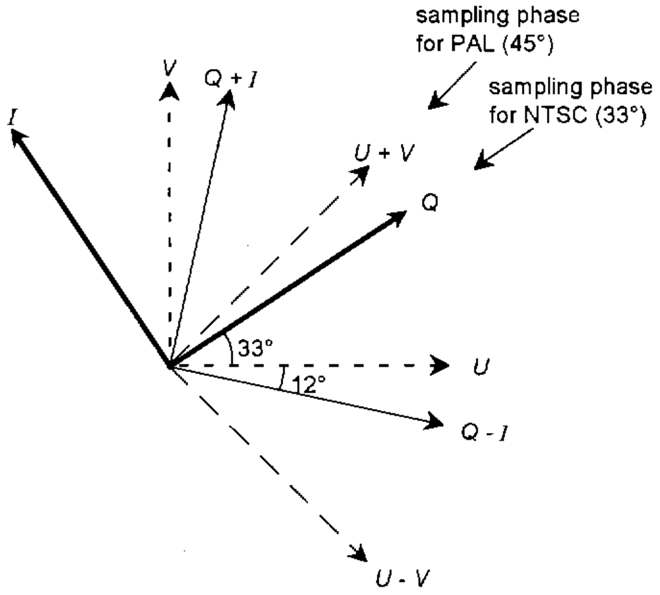


Fig. 16 - The relationship between PAL and NTSC chrominance signals

4.2 Chrominance processing

The chrominance processing in the NTSC-compatible system differs from that in the PAL version for two reasons. Fig. 17 illustrates the coder and de-0 coder chrominance processing for the two systems and the reasons for the differences are described below.

Firstly, the preferred sampling phase of a digital NTSC signal sampled at $4f_{sc}$ is on the I and Q axes instead of on the $U \pm V$ axes. I and Q are the colour difference signals used in NTSC; their relationship to U and V is shown in Fig. 16. To produce a coded signal in the required form, the U and V signals entering the pre-filters of Fig. 3 may be replaced by $Q-I$ and $Q+I$ respectively. This can be achieved by changing the $RGB - YUV$ matrix slightly to introduce a rotation of 12° compared with the PAL case, since $Q-I$ is 12° away from U and $Q+I$ is 12° away from V. Then the vertical chrominance switching action (discussed in more detail below) forms sums and differences of the chrominance signals at its inputs, as in the PAL case; i.e. it calculates $\pm(Q-I)\pm(Q+I)$, which yields $+Q$, $-Q$, $+I$ or $-I$. Alternatively, the same result may be achieved by starting with Q and I at the inputs of the vertical filters, and having a vertical chrominance switch which selects one of the two components (which it may then negate). The first approach has a closer resemblance to the PAL-compatible system, leading to greater hardware commonality between PAL- and NTSC-compatible versions.

Secondly, a different vertical chrominance switching action is required from that of the PAL-compatible system. The switching action must be chosen to generate a combined chrominance signal which, when modulated by f_{sc}^* and operated on by the filter F2 (which resembles a $(\frac{1}{2},-\frac{1}{2})$ vertical filter for

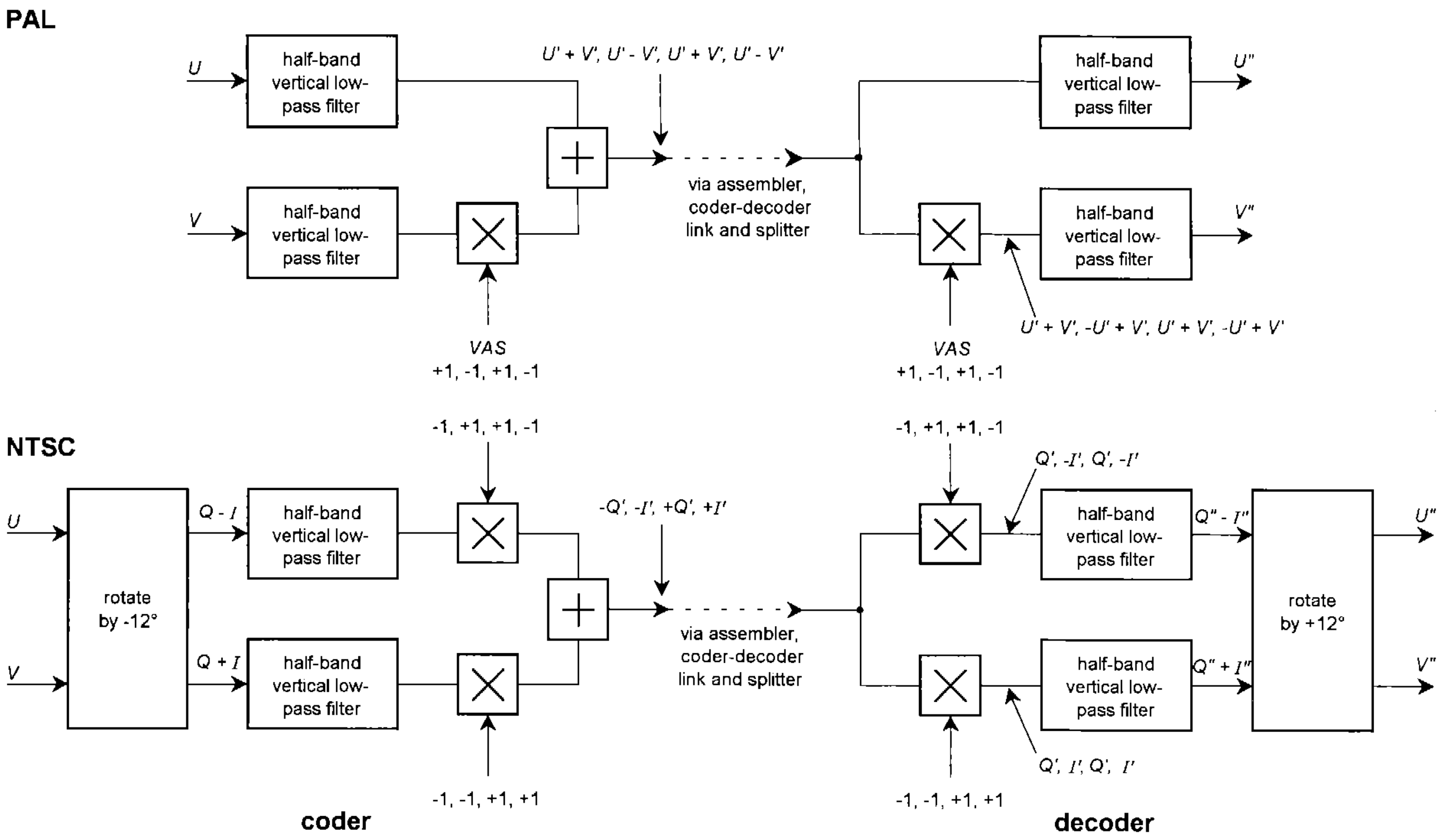


Fig. 17 - Chrominance processing in the PAL- and NTSC-compatible systems
(Annotations show values on four successive field lines; the values repeat every four lines. Dashed quantities (eg U') denote filtered signals.)

Field line	Chrominance signal from switch	f_{sc}* modulation				Signal at input to F2				Output of F2 (ignoring scaling factor)			
Field 1:													
1	–Q	0	+	0	–	0	–Q	0	+Q	+I	+Q	–I	–Q
2	–I	–	0	+	0	+I	0	–I	0	–I	–Q	+I	+Q
3	+Q	0	–	0	+	0	–Q	0	+Q	+I	+Q	–I	–Q
4	+I	+	0	–	0	+I	0	–I	0	–I	–Q	+I	+Q
Field 2:													
1	+Q	0	+	0	–	0	+Q	0	-Q	–I	–Q	+I	+Q
2	–I	+	0	–	0	–I	0	+I	0	+I	+Q	–I	–Q
3	–Q	0	–	0	+	0	+Q	0	–Q	–I	–Q	+I	+Q
4	+I	–	0	+	0	–I	0	+I	0	+I	+Q	–I	–Q

frequencies around f_{sc} as explained earlier), yields a modulation pattern resembling that of a normal NTSC signal sampled on the *I* and *Q* axes. This requirement fully determines the form of the switching action. The switching action has a four-line repeat pattern, unlike the PAL case which repeats every two lines. The table shows the switching action required, and how it results in the desired output from F2 (samples are on a lattice at $4f_{sc}$).

The chrominance switching action is frame-repetitive, because in one frame period both f_{sc}* and the required NTSC chrominance output change sign; therefore the chrominance signal at the input to the f_{sc}* modulator need not change sign from frame to frame. This gives rise to static vertical chrominance aliases when the signal is decoded with a normal NTSC decoder, as distinct from aliases modulated at $12\frac{1}{2}$ Hz in the PAL-compatible system. There are corresponding aliases in the picture from a matching decoder, but at such a low level that it is largely immaterial whether they are moving or stationary.

It should be pointed out that the spectrum of the switched chrominance signal, shown in Fig. 18, differs significantly from that in the PAL case, shown in Fig. 7. In the PAL case, *U* is centred on a carrier at zero vertical frequency and *V* is on a carrier at 144 c/aph. In contrast, in the NTSC-compatible system, the *I* and *Q* signals, in quadrature, are both modulated onto a vertical carrier at odd multiples of 61 c/aph (half of the Nyquist limit for a field, the equivalent of 72 c/aph for a 625-line signal). Thus, they are separated by being in quadrature rather than by being modulated at different vertical frequencies.

In the decoder, the chrominance signals are separated by a vertical quadrature demodulation similar to that in the coder, to form two data streams of *Q–I* and *Q+I* (each vertically subsampled and with the *Q* and *I* components in quadrature). Two vertical low-pass filters remove the repeat spectra caused by the vertical subsampling. The filtered signals are then rotated by 12° to produce *U* and *V* (the rotation may be combined into the *YUV-RGB* matrix).

4.3 Characteristics of the NTSC-compatible system

The most significant difference in performance of the NTSC-compatible system compared with the PAL-compatible system is the reduced horizontal bandwidths of luminance and chrominance. This is a direct consequence of the lower subcarrier frequency used, and hence the lower overall bandwidth available in equipment such as D2 and D3 recorders operating at $4f_{sc}$. The luminance bandwidth, $3f_{sc}/2$, is approximately 5.4 MHz; the chrominance horizontal bandwidth is a third of this figure, approximately 1.8 MHz. Thus the NTSC-compatible system falls a

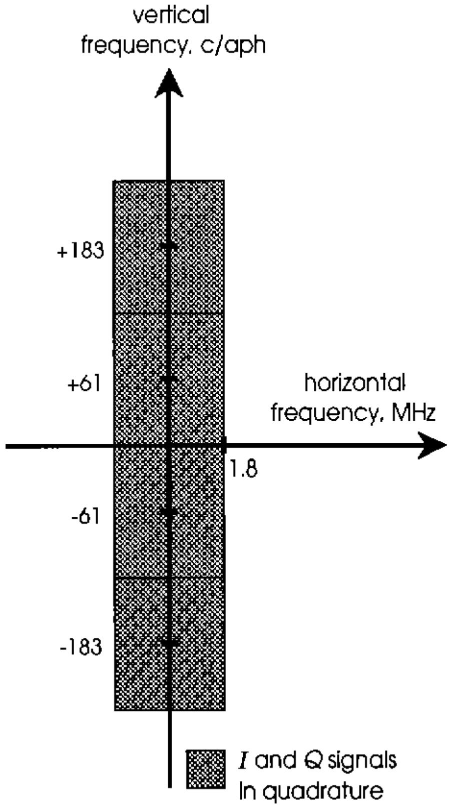


Fig. 18 - The spectrum of the chrominance signal in the NTSC-compatible system

little short of allowing the full luminance bandwidth of CCIR Rec. 601 to be conveyed.

The ratio of horizontal-to-vertical resolution of the NTSC-compatible system is close to the corresponding ratio for the PAL-compatible system, since the ratio of the subcarrier frequencies (approximately 0.81) is similar to the ratio of the number of active lines (approximately 0.85). Therefore, the response of the system remains well matched to a 16:9 display.

The fact that the subcarrier frequency is lower for NTSC compared with PAL allows a wider combing region to be used in the assembler and splitter filters, whilst still limiting the upper end of the region to a frequency (around 5.5 MHz) likely to be passed by all types of studio equipment. (Limiting the combing region to frequencies likely to be always passed ensures that no cross-effects will ever be present.) The wider combing region improves the compatibility of the signal with normal NTSC because the chrominance signal more closely resembles the double-sideband signal of NTSC. One consequence of this is a significant reduction in the appearance of slight luminance-chrominance mis-registration when a normal NTSC decoder is used (discussed in Section 2.2.4). This is because the amplitude of the chrominance signal remains constant for a wider range of frequencies around f_{sc}, since F2 resembles a $(\frac{1}{2},-\frac{1}{2})$ vertical filter over a wider range of frequencies. This is fortunate, because it is not possible to compensate for any mis-registration by applying a fixed relative delay to one chrominance component (as can be done in the PAL-compatible system) because of the different nature of the vertical chrominance modulation.

4.4 Computer simulation of the NTSC-compatible system

Computer simulations of the NTSC-compatible system described above have been carried out. With the exception of the assembler and splitter filters, F1-F4, the filters used throughout were the same as those used for the PAL-compatible system, but scaled for the lower subcarrier frequency. In fact, since the filters were implemented as digital filters at a sample rate of $4f_{sc}$ in both systems, no change in filter coefficients was required. New assembler and splitter filters with a wider combing region were designed, for reasons explained above.

The performance of the system was assessed on test patterns and on a variety of other critical picture material. The reduced horizontal resolution compared with the PAL case was found to be hardly visible on 4:3 test sequences, resulting only in very slight aliasing in areas containing high-frequency detail. This was because the sequences used contained a little energy in the region around 5.4 MHz (the limit of the NTSC-compatible system), but no significant energy around 6.6 MHz (the corresponding limit for the PAL-compatible system). The resolution loss would be expected to be more visible on material originated using wide-band 16:9 cameras.

The picture quality obtained when decoding the signal with a normal NTSC decoder was judged to be marginally better than that of conventional NTSC. The slight improvement was due to the reduction in coarse cross-colour, at the expense of some loss of high horizontal and diagonal luminance resolution. This is similar to the situation with the PAL-compatible system. The only significant impairment was the introduction of vertical chrominance aliasing, visible as a static pattern of coloured horizontal lines in areas of high chrominance vertical detail. This is also similar to the situation with the PAL-compatible system, although, as explained earlier, the chrominance aliases are modulated at $12\frac{1}{2}$ Hz in the PAL case.

Pictures with a quality similar to normal NTSC were produced when a conventionally-coded NTSC signal was decoded using the decoder described here. Fine cross-colour was eliminated, resulting in clean portrayal of luminance at low vertical frequencies up to just over 4 MHz. Cross-luminance was reduced on horizontal chrominance transitions compared with simple NTSC decoding, although it appeared instead on vertical transitions (similar to a line-comb NTSC decoder). These observations are very similar to those for the PAL case.

5. CONCLUSION

This Report has described a new method for conveying a component signal, with quality approaching that of CCIR Rec. 601, as a single signal that may be handled by existing composite PAL studio equipment. The signal resembles conventional PAL below about 5.5 MHz, allowing existing composite mixers and monitors to be used. The coding method is non-adaptive and uses no field delays, being based primarily on horizontal filtering and modulation techniques and the principles of sub-band coding.

Experimental hardware to code and decode the signal has been developed and used for field trials of the system at BBC Television Centre and in an outside broadcast vehicle. These trials confirmed that the signal can be passed through most existing studio equipment with little or no impairment, and that D3 recorders can record the signal without loss. The equipment was demonstrated at IBC '92 and the Montreux ITS in 1993.

A form of the system that is compatible with NTSC has been devised and studied by computer simulation. Its performance was found to be very similar to the PAL-compatible system. The primary difference was a reduction in horizontal bandwidth of about 20% due to the lower subcarrier frequency used for NTSC; this reflects the lower total bandwidth available in $4f_{sc}$-based NTSC studio equipment compared with the PAL equivalent. The operation of the coder and decoder is very similar to that for the PAL case; the only changes are to the sampling and modulation structures used and to the chrominance processing. A perturbed form of NTSC subcarrier is used to allow correct operation of the assembler and splitter. The chrominance processing requires the formation of signals based on I and Q instead of U and V, and uses a vertical chrominance switching action different from that of the PAL case.

The coding system should provide a useful stepping stone to ease the transition from PAL or NTSC to component production for sourcing new distribution methods, and would be particularly helpful when widescreen pictures were handled.

6. ACKNOWLEDGEMENTS

The author would like to thank colleagues at Research & Development Department for their help in the work described here, in particular Ken Boak, Peter Brightwell and Patrick Morrison for their work on the experimental hardware, and John Drewery and Jim Easterbrook for assistance with the theory and software simulations.

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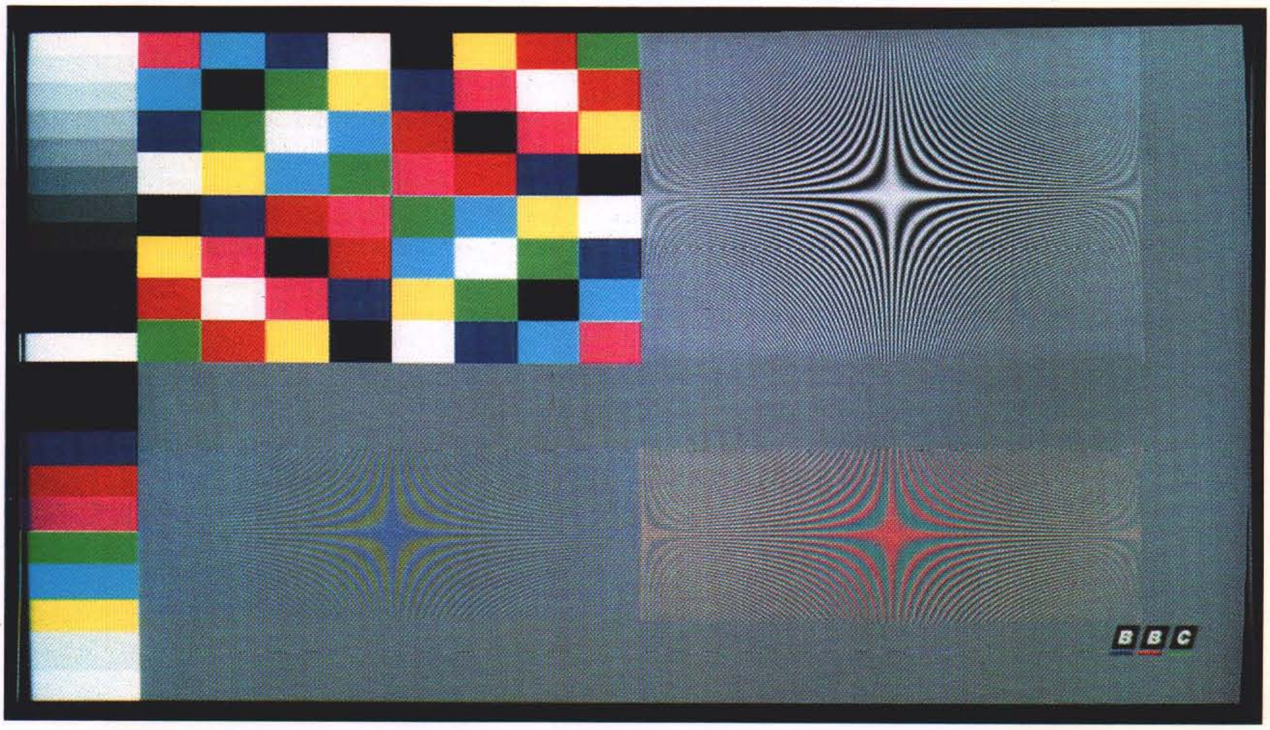
Inventor: Drewery, J.O., Weston, M.
UK Patent No. GB 2045577A.

APPENDIX 1

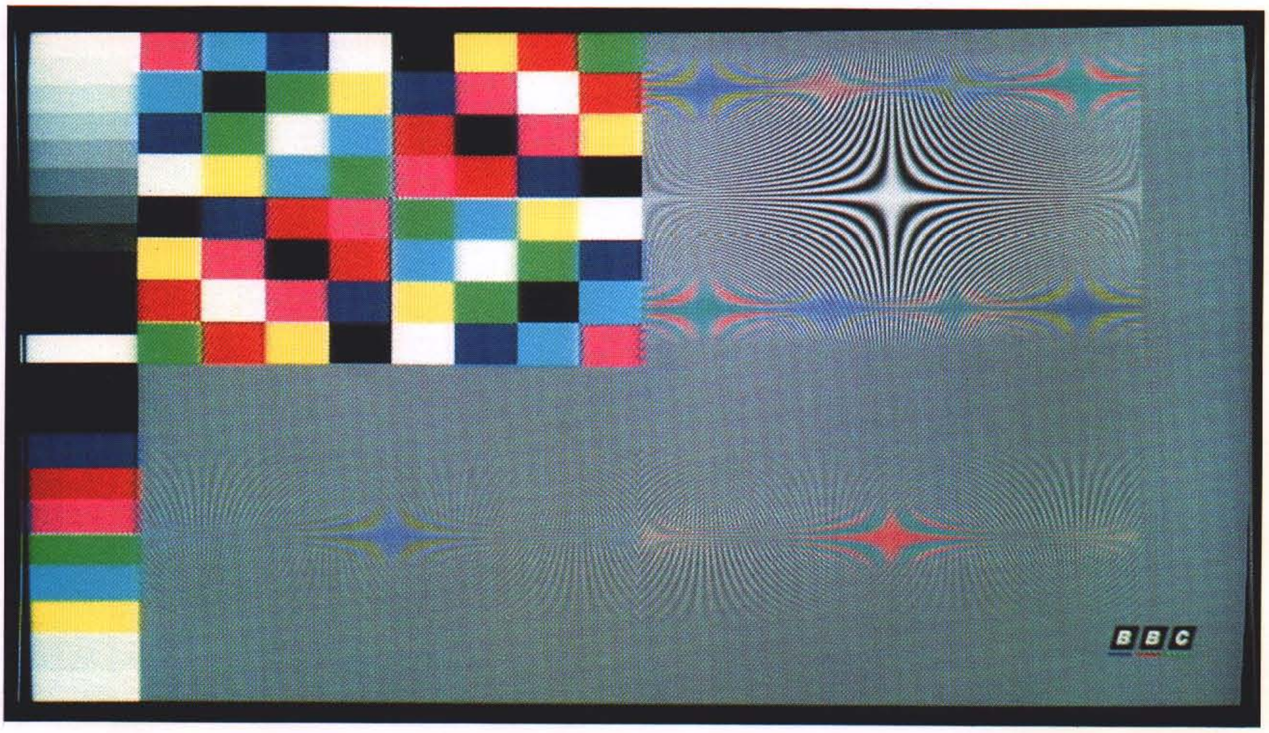
Photographs illustrating the performance of the PAL-compatible form of the Com^3

Figs. A1.1-A1.6 show off-screen photographs of one frame of a 16:9 625-line test pattern processed with various combinations of conventional PAL and *Composite Compatible Component* coding and decoding. The conventional PAL coder used had no notch or other form of filtering in its luminance channel. The conventional PAL decoder had a simple notch filter in the luminance path and did not incorporate a delay line in the chrominance path. This is typical of the PAL coders and decoders currently in use within the BBC.

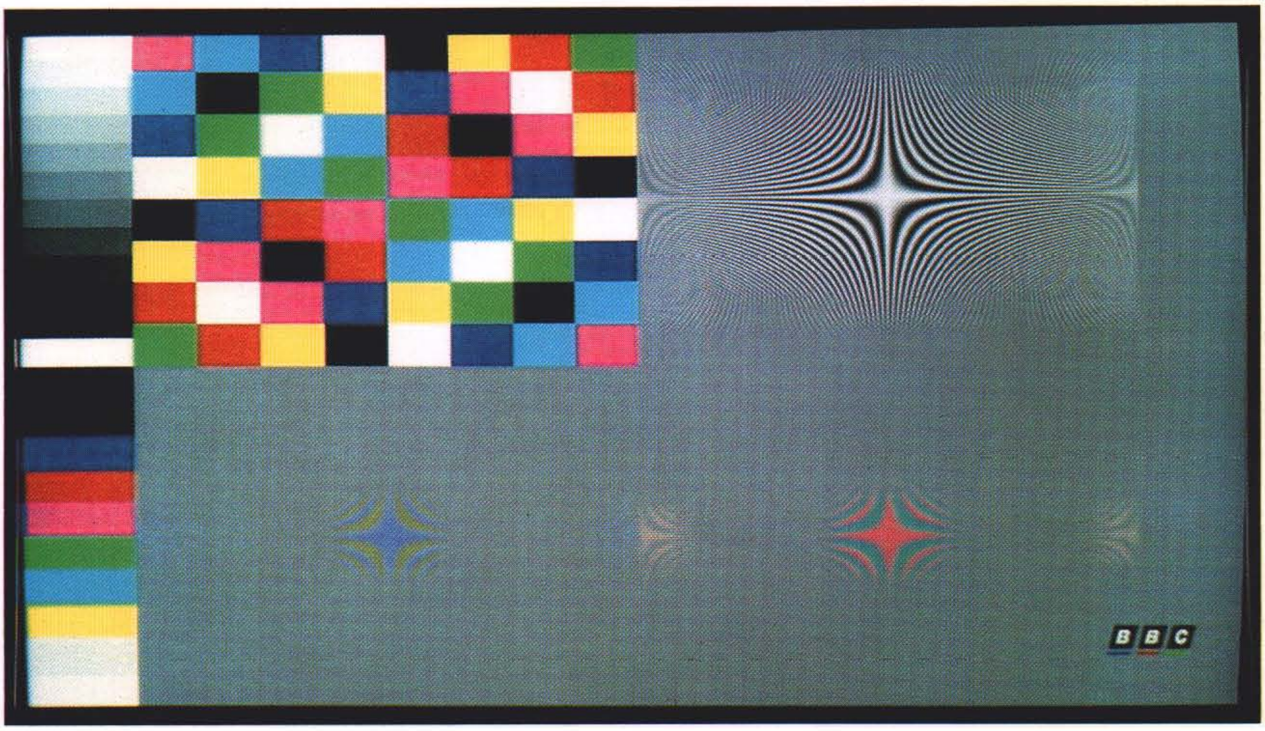
The test pattern shows a Y hyperbolic zoneplate with horizontal frequencies in the range 0-6.75 MHz and vertical frequencies in the range of 0-288 c/aph. The chrominance hyperbolic zoneplates show the signals U (on the left) and V (on the right), and have horizontal frequencies on the range 0-3.375 MHz and vertical frequencies in the range of 0-288 c/aph. The coloured patches show colours from 100% colour bars.



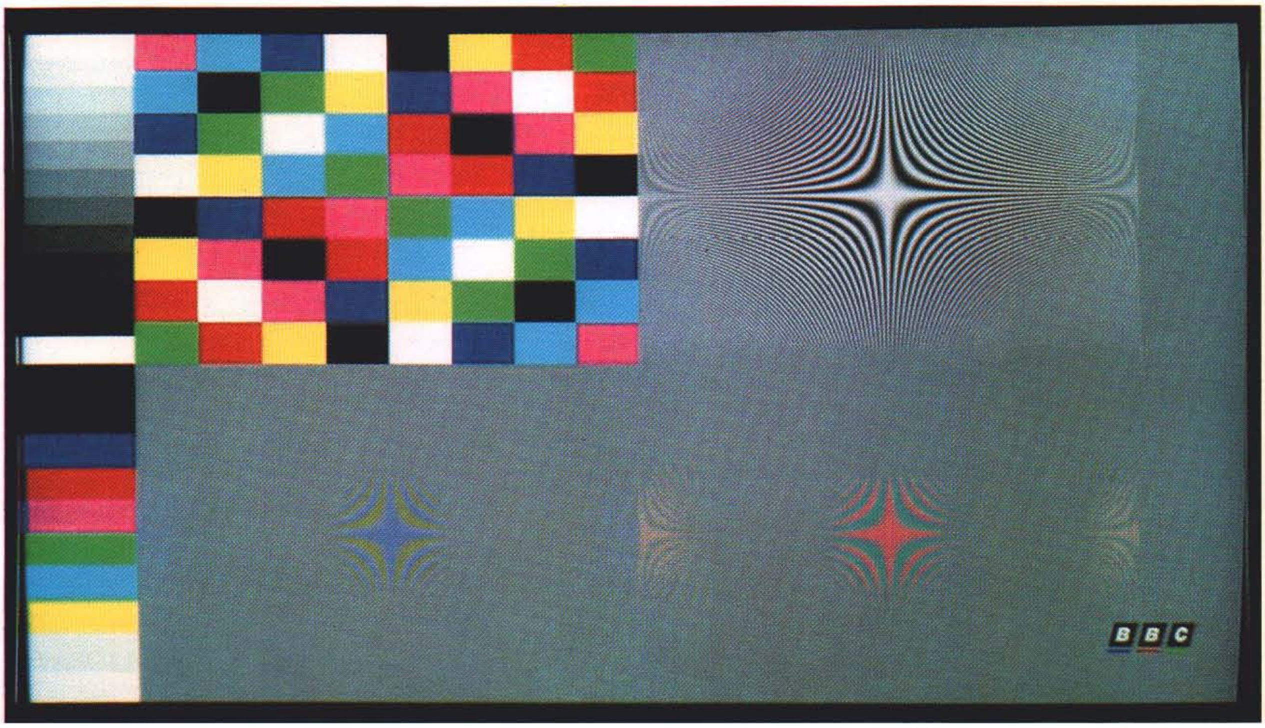
A1.1 Source picture (CCIR Rec. 601, 625-line).



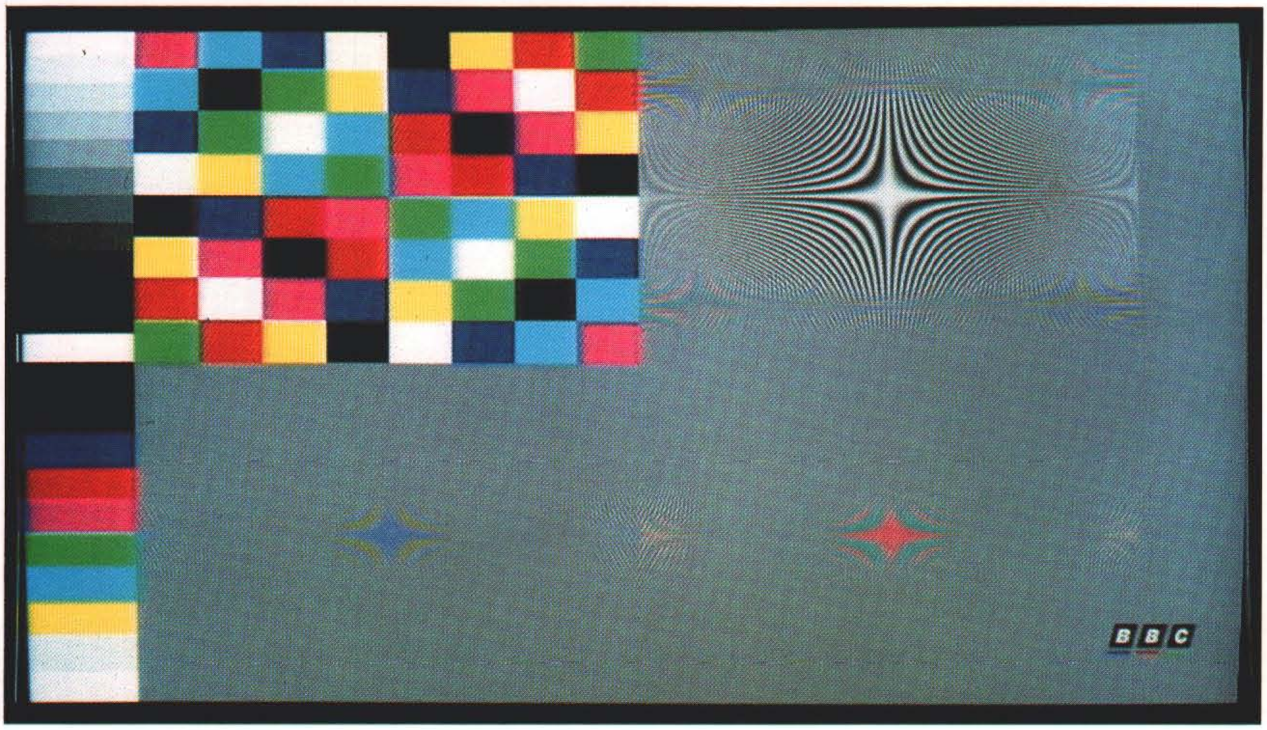
A1.2 Coded and decoded with conventional PAL (5.5 MHz bandwidth).



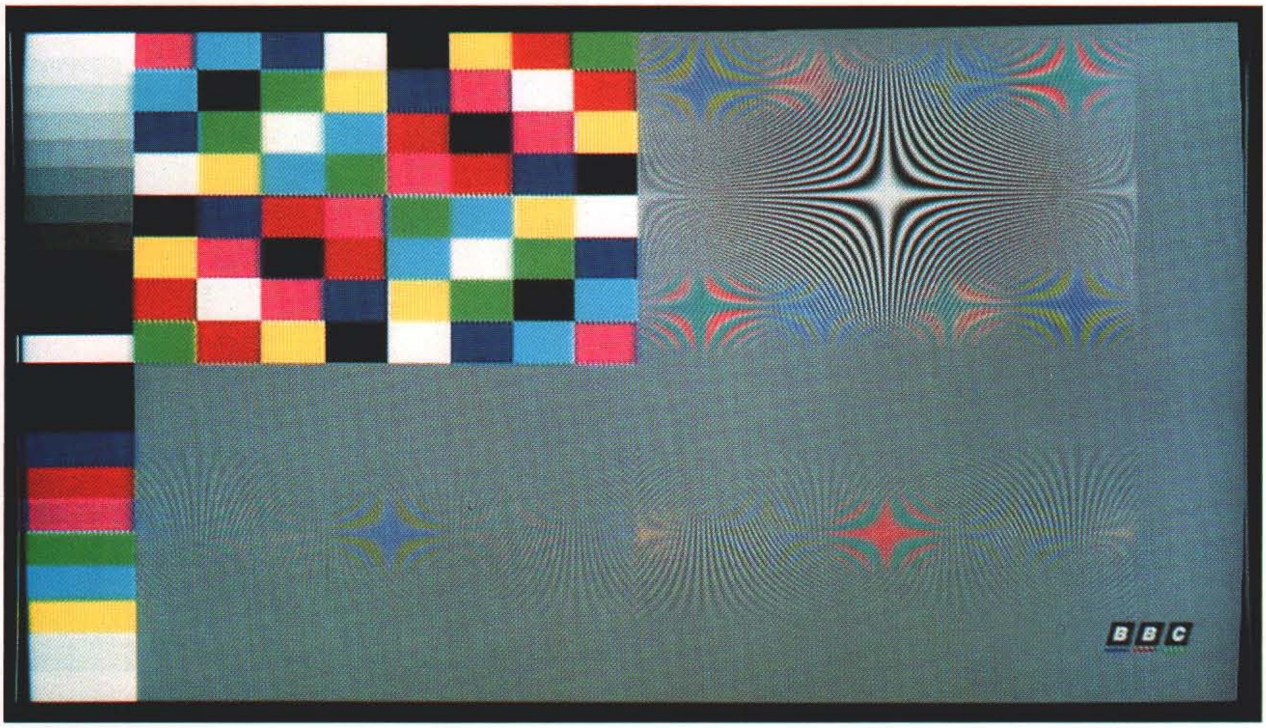
A1.4 Coded and decoded with Composite-Compatible Component coder and decoder (coded signal limited to 5.5 MHz).



A1.3 Coded and decoded with Composite-Compatible Component (full bandwidth coded signal).



A1.5 Coded with Composite Compatible Component, decoded with simple PAL decoder (full bandwidth coded signal).

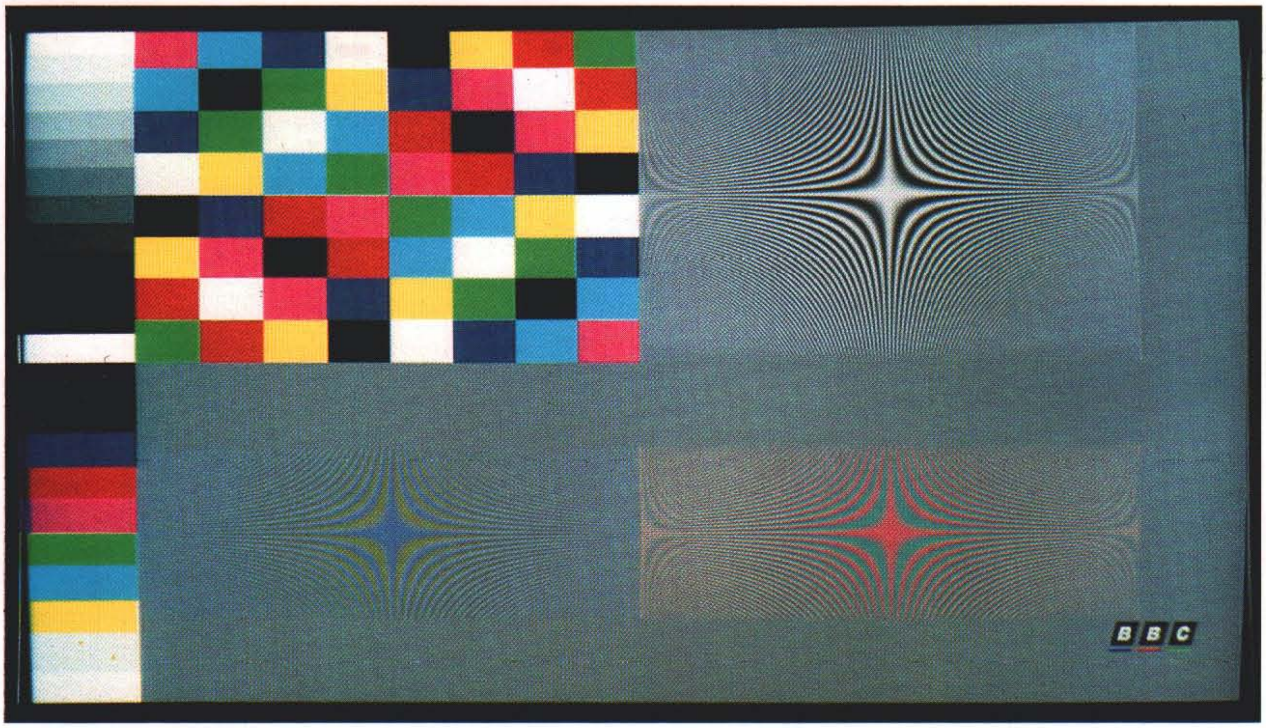


A1.6 Coded with conventional PAL coder, decoded with Composite Compatible Component decoder (5.5 MHz bandwidth).

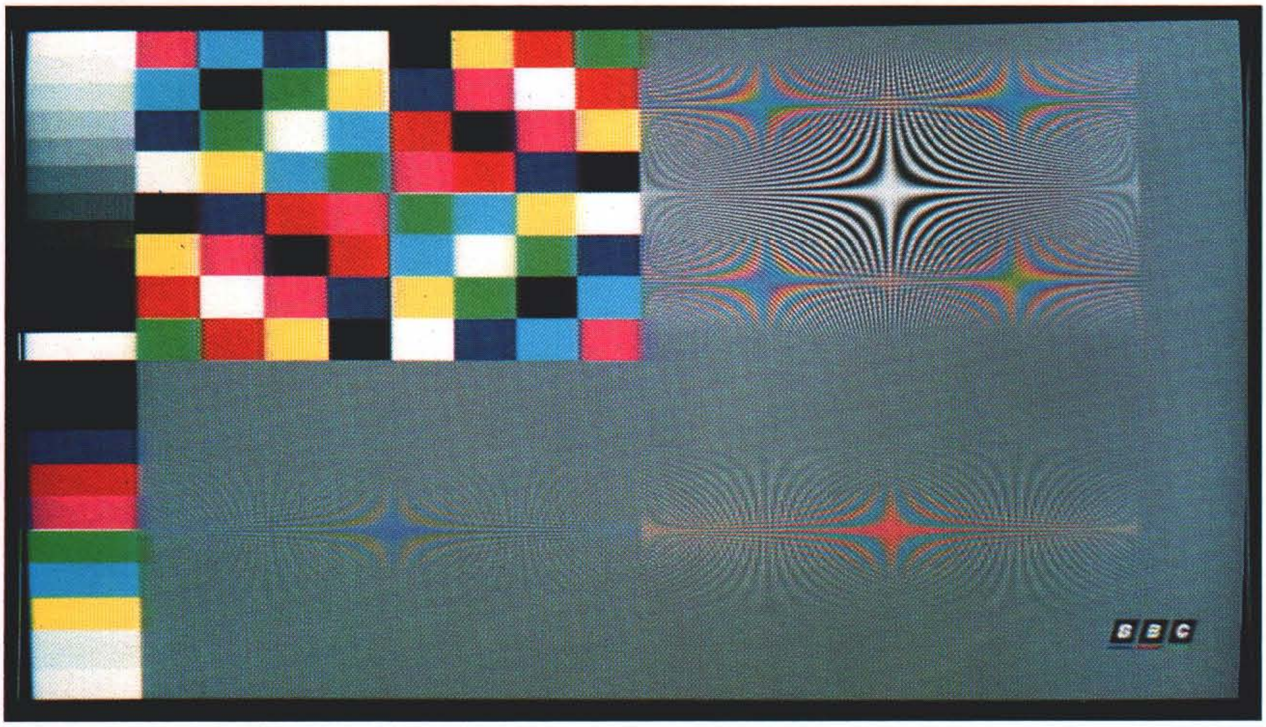
APPENDIX 2

Photographs illustrating the performance of the NTSC-compatible form of Com^3

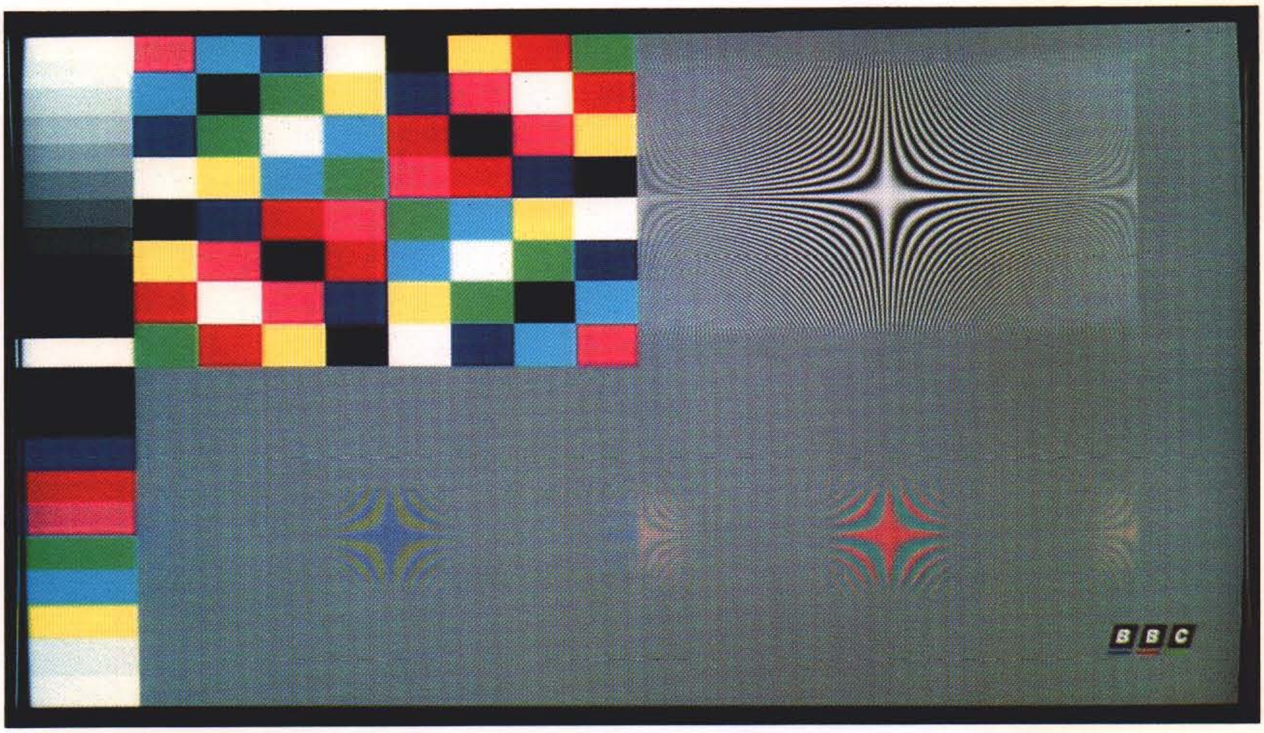
Figs. A2.1-A2.6 show off-screen photographs of one frame of a 16:9 test pattern processed with various combinations of NTSC and *Composite Compatible Component* coding and decoding (the pictures show simulation results carried out with the 625-line test picture shown in Appendix 1, although in all other aspects the simulations corresponded to true NTSC). The NTSC coder used had no notch or other form of filtering in its luminance channel. The NTSC decoder had a simple notch filter in the luminance path and did not incorporate a delay line in the chrominance path, to allow direct comparison with the PAL decoder output shown in Appendix 1. Note that the majority of NTSC decoders in use at present include some form of line or field combing to give improved separation of chrominance and luminance.



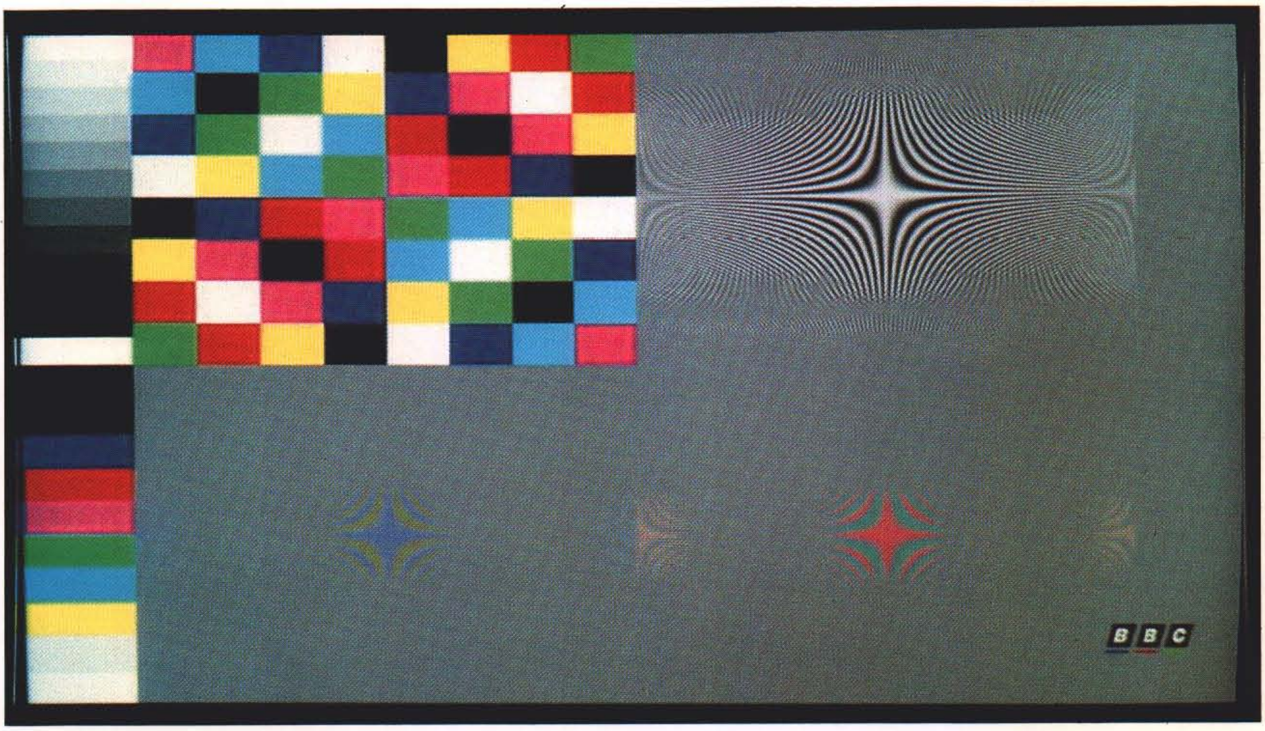
A2.1 Source picture (CCIR Rec. 601, 625-line).



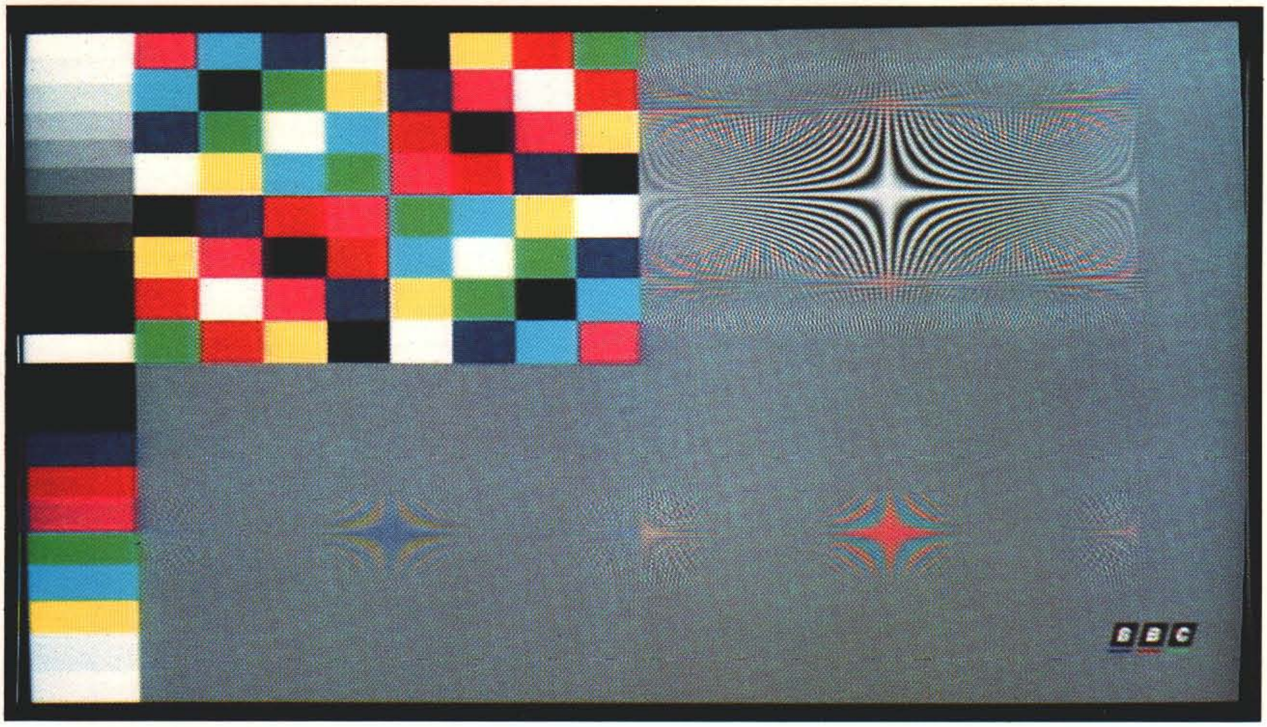
A2.2 Coded and decoded with normal NTSC (5.5 MHz bandwidth).



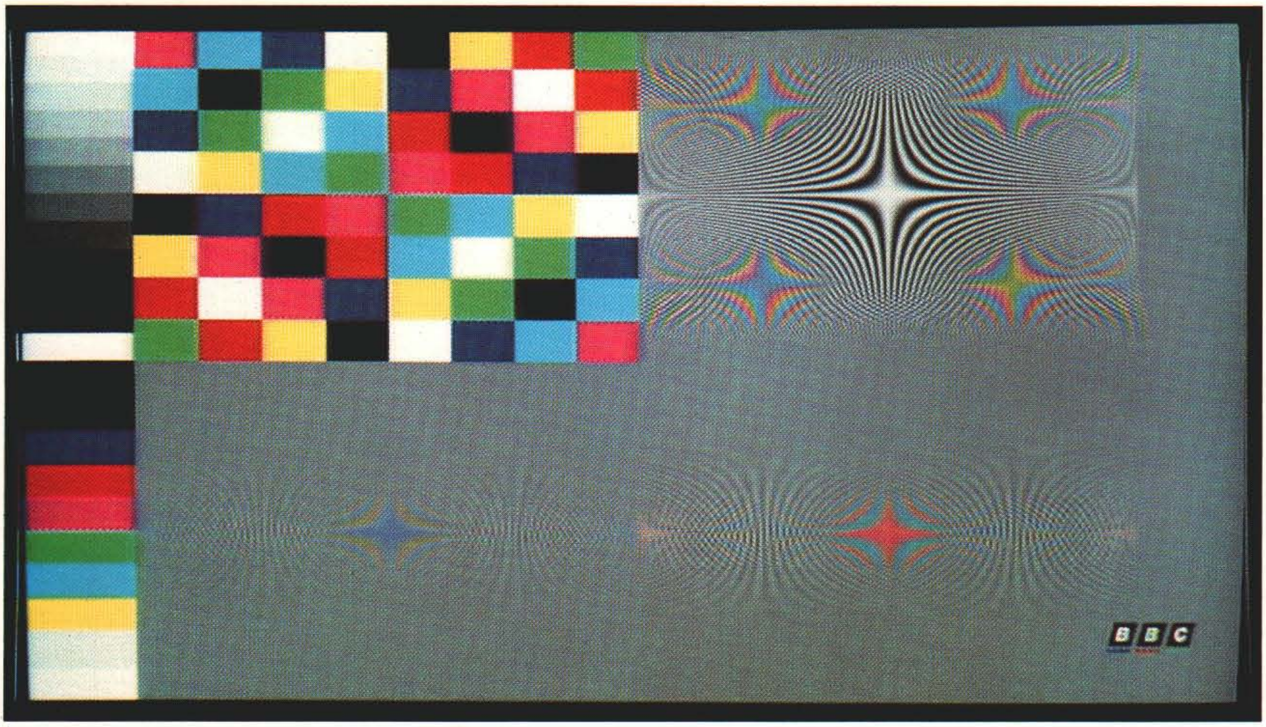
A2.3 Coded and decoded with Composite Compatible Component (full bandwidth coded signal).



A2.4 Coded and decoded with Composite Compatible Component coder and decoder (coded signal limited to 5.5 MHz).



A2.5 Coded with Composite Compatible Component, decoded with simple NTSC decoder (full bandwidth coded signal).



A2.6 Coded with normal NTSC coder, decoded with Composite Compatible Component decoder (5.5 MHz bandwidth).

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